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Coastal Inundation Risk Analysis Using Bayesian Network

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Abstract

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Recently, natural hazards have been more unpredictable with increasing frequency and strength due to climate change. Especially, coastal areas could be more vulnerable in the future because of climate change. In the case of South Korea (hereafter, Korea), the country is surrounded by ocean and there are many large cities along the coastal areas. Thus, a series of hazard prevention plans are necessary in the coastal areas. However, prior to formulating a plan, the first step would be to find risk areas. The local characteristics of coastal areas should also be considered in order to find vulnerable areas. Therefore, the objective of this study is to find vulnerable areas that could be damaged

by coastal hazards caused by typhoon and rainfall when considering the local environment.

The contextual scope of this study was narrowed down to coastal inundation cause by typhoon and rainfall. The spatial scope was set up as an administrative district located close to the coastline. Physical and socio-economic characteristics were considered to evaluate the risk in coastal areas. 'Risk analysis' was carried out through the combination of 'possibility of hazard' and the 'level of damages'.

Risk analysis was implemented by using Bayesian Networks (BNs), which is a stochastic-statistics method. BNs are based on Bayes' Rule, which is calculated by using prior probability to estimate posterior probability. In other words, after creating a network from prior information, the posterior information is calculated by using the Bayesian method. Thus, 'the possibility of coastal inundation' caused by typhoon and rainfall was estimated by using the Bayesian method and 'the level of damage' was estimated by coordinating the probability result of inundation with each of 4 socio-economic dimensions, which are human, infrastructure, environment and socio-economic. 'The level of damage' was also estimated by using the Bayesian technique. As a result, the total risk of risk analysis was calculated by summing up the result from 4 dimensions.

According to the result of the study, the Songdo area (Incheon), the Baegot development-prearranged area (Siheung) and the lake region (Assan) were shown to be the vulnerable areas. Songdo needs special coastal management in the future since a study showed that Songdo would become a vulnerable area due to sea level rise and other coastal hazards. Although the Baegot development-prearranged area has not been developed yet, a coastal development and hazard plan should be set up for preventing possible natural hazards. The lake region consists of an agricultural area, experiencing frequent flooding. Thus, the lake region must be protected to minimize damage to agriculture due to coastal inundation.

This study, however, has a limitation on data since not all of the past 30 years of information could be used as an input data. Also, dividing the coastal inundation events into three categories was random. Although with these limitations, this study has academic and practical significance. First, the study considered physical and socio-economic variables at the same time, which has not been examined in prior studies. Second, the Bayesian Networks (BNs) were used to find the risk areas, which were not usually used in domestic studies.

BNs also allow us to consider many variables, reflecting complicated and diverse environment such as coastal area, and to illustrate the statistical analysis into a spatial result. Since the research required both physical and socio-economic characteristics in evaluating risk analysis for coastal cities, BNs seemed to be a suitable method. In conclusion, the use of Bayesian Networks in risk analysis could be applied to manage coastal cities, and as illustrated in this study, the Integrated Coastal Zone Management (ICZM) of Korea.

Keywords: coastal hazards, coastal area, risk analysis, Bayesian Network, typhoon, rainfall.

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1. Introduction

1.1 Research Background and Objective

Natural hazards have influenced the natural ecosystem and human society for a long time. Recently, natural hazards are more concerned with climate change, which is the most important worldwide. Natural hazards have been more unpredictable with increased frequency and strength than before because climate change has affected hydrological, meteorological, oceanographic and geological aspects of natural hazards. Thus, damages or losses due to natural hazards and climate change could be greater in the future.

Especially, coastal areas are more vulnerable to risk than inland areas due to climate change impacts such as sea level rise and increased rainfall. Meanwhile, coastal areas have been a part of human society and natural ecosystems for a long time. Thus, coastal areas have many interests for humans. For example, there are many large cities such as New York, Sydney, Tokyo, Shanghai, Amsterdam, Bangkok and Jakarta are located in coastal areas. Coastal areas house 80% of the world population. Thus, coastal areas are very important regions from a socio-economic context. Moreover, coastal areas can be more affected by damages or losses due to natural hazards, which have also been more unpredictable.

In the case of Korea, the country is surrounded by oceans on three sides and has experienced damages and losses by inundation every summer season due to coastal hazards such as typhoon and rainfall. The damages and losses would also be greater because the frequency and strength of natural hazards are more unpredictable due to climate change in the future. Thus, coastal areas have to be protected from these risks through proper planning and management.

The first step is to find areas with inundation risk prior to setting any plan. Vulnerabilities and risks have different characteristics for each region even if the same vulnerabilities and risks are experienced in different coastal areas. Vulnerability is defined as the probability in which a subject could be damaged by a hazard. ‘Risk’ is defined as the degree in which the subject would be actually damaged. For example, when a typhoon comes to an area, the typhoon itself is the hazard. Inundation vulnerability comes differently according to the area due to regional characteristics. The damage degree of inundation varies in different areas, which is called risk. In other words, risk analysis reflects features of the areas and should be implemented to find risks and vulnerable areas, and not to find vulnerability assessment. Risk analysis could be described as a combination with ‘probability/possibility of hazard’ and ‘degree of damage’.

When risks from coastal inundation are analyzed, coastal characteristics have to be considered in order to reflect the features of coastal areas. Coastal areas have two combined characteristics, which are the socio-economic character of human society and the physical and natural ecosystem. Risk analysis needs a proper technique and methodology to reflect the features of coastal areas that have a complicated process. Therefore, various indicators could help to reflect and should be considered in the process of coastal areas. The relationships of these indicators are very important.

The results of risk analysis are factored into the probability of hazard and should be emphasized. Risk analysis should be implemented by the stochastic-statistics method because of the importance of probability and not implemented by a physical model or analysis based on a qualitative index. Although a physical model and analysis using a qualitative index have significant results, a physical model illustrates binary results, which have limitations and cannot be trusted 100%. An analysis using a qualitative index does not achieve qualitative results, which questions index trustworthiness.

Therefore, this study uses Bayesian Networks (BNs), which is a stochastic-statistics method based on Bayes' Rule. BNs have some merits. First, BNs consider many variables at the same time and visualize the network setting among many variables, which is helpful to easier understand than a physical model. Second, BNs consider future uncertainty because of the results of probability and possibility even if the data is insufficient. Third, BNs have description characteristics to help implement policies in comparison to other methods.

According to these advantages, BNs can be used in many fields and BNs are proper for analyzing coastal areas, which have a complicated natural process. Therefore, the objective of this study is to find the risk areas by coastal inundation using BNs, which is a stochastic-statistics method in a coastal area through the contextual methodology of risk analysis. The risk analysis using BNs could be useful to manage coastal cities and to manage the Integrated Coastal Zone Management (ICZM) in Korea.

1.2 Flow of the research

Flow of the research is followed by Figure1. Chapter 1 is introduction included background and objective. Chapter 2 introduced about definition of keywords used in the research from literature reviews. Materials and method are described in chapter 3. It includes spatiotemporal and contextual scoping and setting data. It would be described about dataset which is used to evaluate the risk caused by coastal hazards, and how to find risk areas is described. This research used ‘Risk analysis’ which is kinds of conceptual model. It is implemented by combination with ‘probability of hazard’ and ‘its consequence’. ‘Probability of hazard’ could be estimated by using physical indicators and ‘its consequence’ was calculated by using socioeconomic indicators. And Bayesian Networks was made by using these indicators. And the total risk was the results of the research, which was showed at chapter 4. In conclusion, it could be recognized that which areas more vulnerable or risk due to coastal inundation.

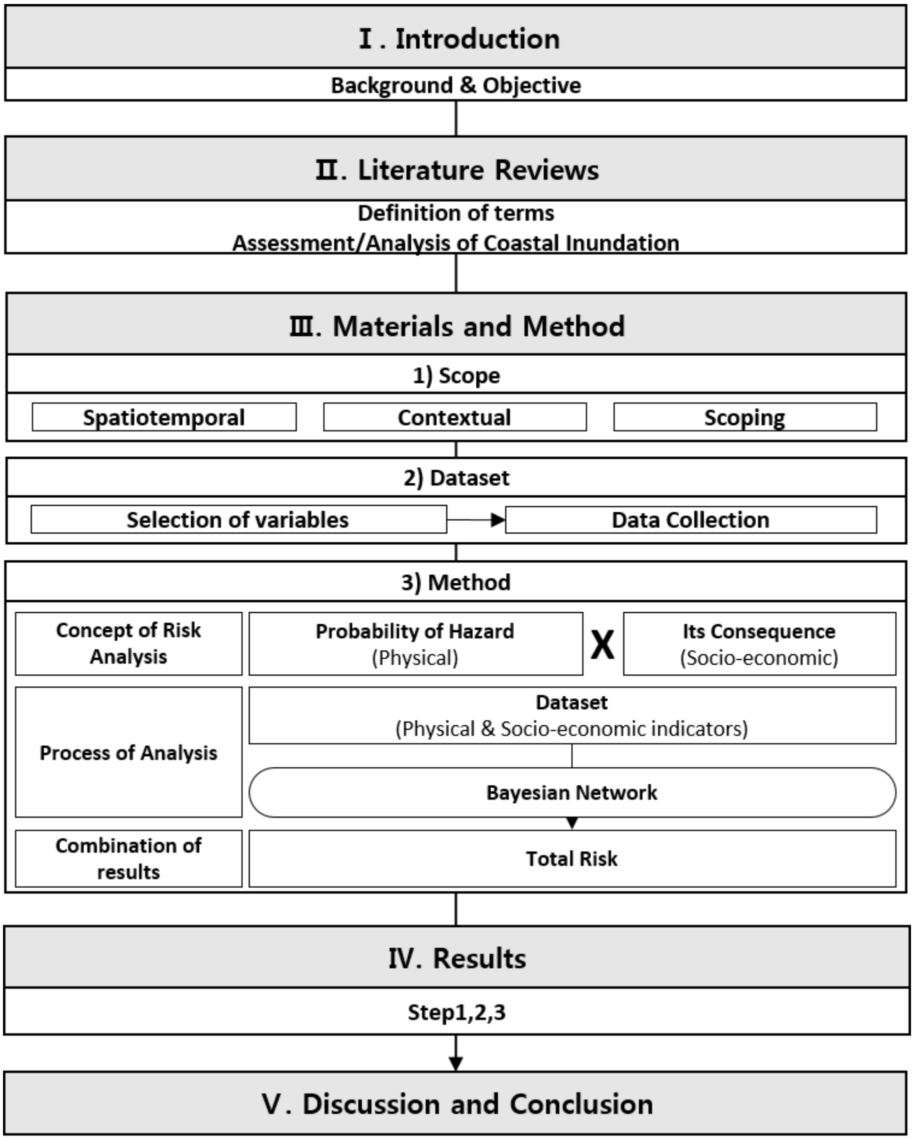


Figure 1. Flow of the research

2. Literature Reviews

2.1 Definition of terms

2.1.1 Coastal Inundation

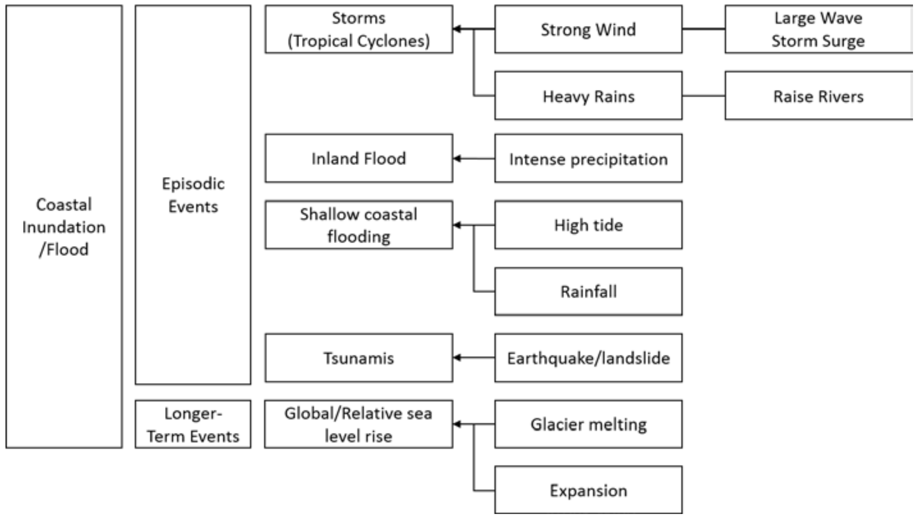


Figure 2. Coastal Inundation/Flood (Reconstitution from NOAA, 2009)

Coastal hazard is defined as a physical phenomenon and causing massive damage and loss of human life and the environment of the coastal zone (en.wikipedia.org). Coastal inundation or flooding is a situation of coastal hazard and it can be divided into four as cause (Figure 2); inundation of storm surge caused by tropical cyclones such as typhoon, inland flood due to heavy rain, shallow coastal flooding called surface flooding when heavy rain comes along with change of sea level, inundation caused by the tsunami due to earthquake or landslide.

First of all, the most important flooding by the storm surge caused by the typhoon is the fact that typhoon accompanied by strong winds and huge amounts of rain. And storm surge could be estimated by wind set-up, sea-pressure set-up, wave and tide. So, when the typhoon comes, storm surge strong is happened by strong wind, low-pressure, wave and tide. And it accompanied by heavy rain, so inundation or flooding is occurred. Second, there is a flooding caused by heavy rain. Coastal cities have inland areas likewise other inland cities do. These areas could be flooded by heavy rain or rainfall. Third, coastal areas could be flooded by rainfall along with rising sea-level. It is usually occurred at impermeable zone because the situation results from overflow of the drainage at urban areas. So, the flood damage can be weighted according to the degree of the water level due to tide and wave height when the rains came. When the rainfall comes along with higher sea-level, inundation is happened since the runoff could not escape and overflow of drainage areas.

Lastly, inundation caused by rising water level during tsunami is a series of water waves caused by the displacement of a large volume of a body of water.

Earthquakes, volcanic eruptions and other underwater explosions, landslides, glacier calvings, meteorite impacts and other disturbances above or below water all have the potential to generate a tsunami (en.wikipedia.org).

From to past, tsunami has not been occurred in Korea. Although there are some experts to expect that there are plenty of possibilities, this research does not consider inundation caused by tsunami.

http://www.escp.org.uk/flood-risk www.newssc.co.kr

Figure 3. Examples of coastal inundation/flooding

2.1.2 Risk Analysis

Risk is defined with damage loss possibility of some value in dictionary. For example, a result from purchasing an A stuff and do not buying the B stuff when you want to buy two things means that it has to be dealt with the risk of not buying one stuff. These definition usually used in Social and Economic.

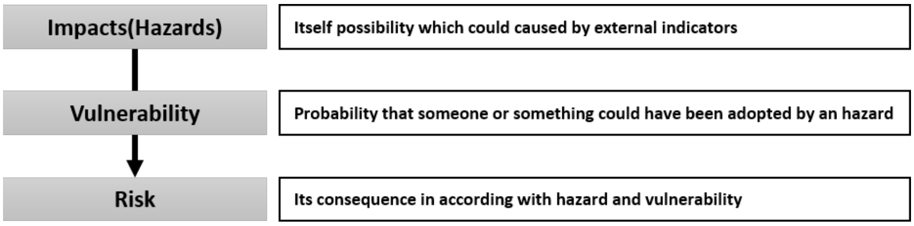


Figure 4. Concept of hazards, vulnerability and risk

In disaster, the risk could be defined that possibility of hazard and its consequences when a hazard or impact factor is occurred. The concept of risk usually used, separated with impact and vulnerability. Impact means a phenomenon of hazard such as typhoon or rainfall and it is a possibility of the hazard itself. And vulnerability is possibility that a subject could be affected by impact of hazard. Lastly, risk could consider degree of damage further one step.

For example a typhoon, typhoon is a hazard itself and it just defined with impact. If a typhoon comes A zone and B zone at the same time, which zones would be affected by it more is the vulnerability. If a zone is lower land than B zone, A zone could be more affected by inundation caused by typhoon. So it is vulnerability and it would appears differently by regions and objects.

Risk is finding its consequences which is degree of damage further one step of vulnerability as mentioned. For example, even though we find that B zone is vulnerable than A zone, we couldn't know how B zone is risk and how much damages affected with only information of vulnerability. In other words, even though we already know which object is affected by impacts or hazard, concept of risk is needed in disaster, since we couldn't know how the area is damages and got losses.

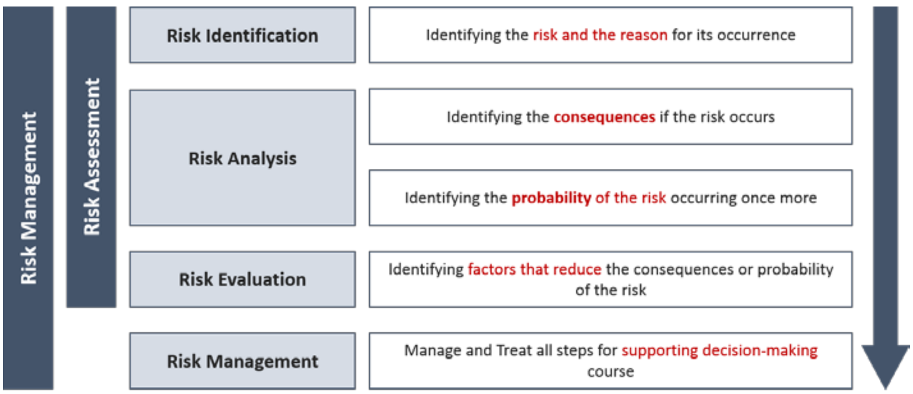


Figure 5. Steps of Risk Management

Risk could be described by combination with possibility of hazard and its consequences which means degree of damage. It is called as ‘risk analysis’ (Table 1). Risk analysis is a step of ‘risk management’ as showed at Figure 5 and it is ultimately a basis step of finding the risk area or factor from a hazard and disaster.

Table 1. Concept of Risk for Risk Analysis

Literature or Homepage	Concept of Risk
ISO 31010 (2009)	a combination of the consequences of an event (hazard) and the associated likelihood/probability of its occurrence
UKCIP (2003)	the combination of the probability of a consequence and its magnitude
Council of the EU (2011)	combining the consequences of a hazard with the likelihood of its occurrence
Elisabeth A. Bowering et al. (2013)	Risk = Probability of hazard * Consequence
en.wikipedia	Risk = Probability of accident occurring * expected loss in case of the accident
Queensland Government (2013)	the frequency of a hazardous event occurring relative to the consequences of the event

2.1.3 Bayesian Networks (BNs)

2.1.3.1 Bayes' Rule

$$P(A|B) = \frac{P(A) \cdot P(B|A)}{P(B)} \tag{1}$$

This research implemented the coastal inundation risk analysis using Bayesian Networks (BNs) which is kind of stochastic-statistics method. Bayes' Rule should be recognized already to understand BNs because it is based on Bayes' Rule. Bayes' Rule is a probability theory which is developed by Bayes Thomas. The theory is about showing relationship between the prior probability and the posterior probability of random variable. According to the Bayesian probabilistic interpretation, Bayes' Rule is how to obtain the updated posterior probability when the new evidence is presented. The relationship between prior and posterior probability is showed at Equation 1 according to Bayes' Rule.

P(A), P(B) are prior probability of A, B each. P(A|B) is the posterior probability of A when B is applied. P(B|A) is called a likelihood which means the idea that something is likely to happen or to have happened (en.wikipedia.org). In other words, it is to find B which is likely A. Furthermore, it is the B which makes the A the biggest value.

If A is the target to be calculated uncertainty and B is the target to be observed, the probability of A would be changed P(A) to P(A|B) after probability of B is observed. Bayes' Rule provides the method of calculation at that time.

2.1.3.2 Bayesian Networks

Bayesian networks (BNs) is basically based on Bayes' Rule as mentioned already. It is made by Pearl, emphasizing three characteristics (2003); (1) the subjective feature of the input data, (2) depending on Bayesian criteria as the basis for updating information, (3) the distinction between cause and result. These things are based on the dissertation of Thomas Bayes in 1763.

From these characteristics, Bayesian Networks (BNs) has some advantages. First of all, at the Bayesian Networks (BNs), there is an effective algorithm to perform leaning and reasoning. Bayesian Network to model a set of variables such as audio signal or protein permutation is called 'dynamic Bayesian Network'. Generalizing Bayesian Networks (BNs) is called ‘influence diagram’ which is available to present and obtain the answer under uncertainty.

Second, it is probabilistic graphical model that represent the dependency among variables. Also it is called formally a Directed Acyclic Graph: DAG) which consists of nodes and arcs like Figure 6. Nodes of each graph indicate each variables and arcs which links nodes present the conditional dependency among variables. Since the network among nodes and arcs is visualized as acyclic graph, it is easier to understand than other model.

Third, it could be applied to use many variables or indicators as nodes. And the links among variables could be set up for user. So, it could be applied diverse fields from natural system to social activities.

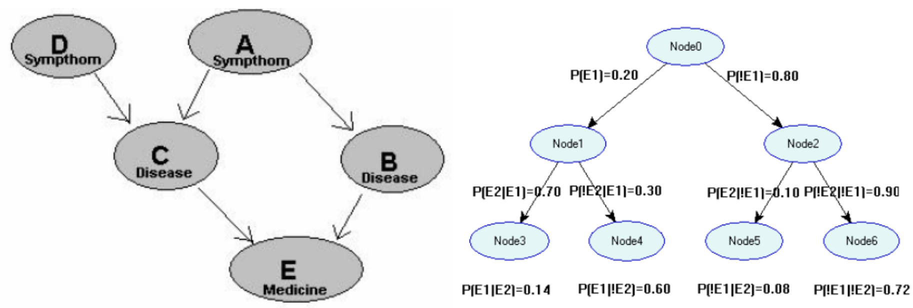


Figure 6. Examples of Bayesian Networks (BNs)

2.2 Assessment/Analysis of Coastal Inundation

2.2.1 Assessment/Analysis of Coastal Inundation

At this section, let's introduce how to assess or analysis of coastal inundation in foreign and domestic. As mentioned already, coastal inundation could be generally divided by four according to cause of events. But, in this research, coastal inundation is divided by two largely which are inundation caused by tropical cyclones such as typhoon in a short time and inundation caused by rainfall in a long time.

2.2.1.1 Caused by Typhoon

For assessment or analysis of inundation due to typhoon, most studies are implemented using physical model. Most studies which implemented coastal inundation assessment or analysis using physical model shows usually the effecting extent or boundary of inundation as calculating the storm surge of tsunami or tropical cyclones. Physical model which used in evaluation of coastal inundation exist variously from two-dimensional to three –dimensional analysis model. Storm surge is determined by combination with four set-up which are general tidal change, wave set-up due to typhoon, wind set-up due to strong wind and set-up of low sea-pressure (Kim et al. 2007).

These studies have limitations that coastal inundation is only evaluated by storm surge caused by typhoon. These studies underestimate that storm surge is only considered coastal inundation analysis when the typhoon comes. In other words, existed studies could not consider coastal inundation caused by typhoon due to rainfall because typhoon contains strong wind and heavy rain. And exited studies evaluated coastal inundation only using physical model. The results after using physical model in boundary or extent of inundation area and it couldn’t present degree of damage. The result is presented partially as non-hazardous area and hazardous area. It is not actual and has uncertainty because it couldn’t be said that non-hazardous area is actually not risk. So, only using physical model has a limitation contains uncertainty of the result.

2.2.1.2 Caused by Rainfall

In contrast to coastal inundation caused by storm surge due to typhoon, there are general events caused by rainfall which are flooding due to rainfall in short time and along with water level change. Coastal area has a characteristic which is close to sea and these areas are sensitive to change of sea-level. So, at coastal area, coastal inundation risk analysis or assessment has to be considered sea-level change. For example, if rainfall comes when the tidal range rose to the highest, the damage of coastal area is bigger than usual day.

Researches that evaluate the coastal inundation or flooding due to rainfall are being implemented assessment and analysis using land cover or land use, drainage information and soil data which expressed well the characteristics of inland area. Lots of studies would be analyzed about coastal inundation using physical model and statistics method. Also, there is a study that coastal inundation caused by rainfall is evaluated considering tidal range.

2.2.2 Variables Related of Coastal Inundation

Variables which used to analyze or evaluate about the coastal inundation and flooding could be divided as causes such as typhoon and rainfall in this research. Coastal Inundation evaluation caused by typhoon almost contains variables which used to estimate storm surge. And coastal flooding evaluation caused by rainfall usually used precipitation, soil information, land use, land cover and drainage data etc. Variables as mentioned above are showed at Table 2 and Table 3.

Table 2. Variables about coastal inundation/flooding due to storms from typhoon

Variables	Author(year)
Tide	Hiroyasu Kawai et al(2005), S.R. Moon et al(2005), J.J Yoon(2006), D.S. Kim et al(2007), J.G. Kim et al(2009), S.Y. Kim(2009), C.K. Kim(2010), Y. Gao et al(2013), Angelica Murdukhayeva et al(2013), Prasad K. Bhaskaran(2013), G. R. Brakenridge(2013), Elisabetta Genovese & Valentin Przyluski(2013), Zhaoqing Yang et al(2014)
Wave	D.S. Kim et al(2007), S.Y. Kim(2009;2010), Junior Darsan et al(2013), Prasad K. Bhaskaran(2013),
Wind	Hiroyasu Kawai et al(2005), S.R. Moon et al(2005), D.S. Hur(2006), J.J Yoon(2006), D.S. Kim et al(2007), J.G. Kim et al(2009), S.Y. Kim(2009), C.K. Kim(2010), Elisabetta Genovese & Valentin Przyluski(2013),
Sea-pressure	Hiroyasu Kawai et al(2005), S.R. Moon et al(2005), D.S. Hur(2006), D.S. Kim et al(2007), J.G. Kim et al(2009), C.K. Kim(2010), Elisabetta Genovese & Valentin Przyluski(2013),
Sea level rise	J.G. Kim et al(2009), Angelica Murdukhayeva et al(2013), Zhaoqing Yang et al(2014)
Storm surge	S.R. Moon et al(2005), J.J Yoon(2006), D.S. Hur(2006), D.S. Kim et al(2007), J.G. Kim et al(2009), Angelica Murdukhayeva et al(2013), Junior Darsan et al(2013)
Elevation	J.G. Kim et al(2009), Angelica Murdukhayeva et al(2013), Junior Darsan et al(2013)

Water Depth	S.R. Moon et al(2005), J.J Yoon(2006), D.S. Hur(2006), D.S. Kim et al(2007)
Water level	J.G. Kim et al(2009), Angelica Murdukhayeva et al(2013)

Table 3. Variables about coastal inundation/flooding due to rainfall

Variables	Author(year)
Precipitation	Y.M. Lee & C.S. Lee(2004), J.M. Lee et al(2006), H.H. Yoo et al(2006), K.I.Son & M.C. Kim(2010), T.U. Kang & S.H. Lee(2012) Lian, J. J. et al(2013), Wang et al(2013), Ellis, J. Bryan et al(2014), Thompson et al(2014)
Tide	Y.M. Lee & C.S. Lee(2004), Lian, J. J. et al(2013), Wang et al(2013)
Wind	K.S. Tan et al(2008), Thompson et al(2014)
Sea-pressure	K.S. Tan et al(2008), Thompson et al(2014)
Sea level rise	Thompson et al(2014)
Storm surge	H.H. Yoo et al(2006), Ellis, J. Bryan et al(2014), Thompson et al(2014)
Elevation	J.M. Lee et al(2006), H.H. Yoo et al(2006), Lian, J. J. et al(2013), Ellis, J. Bryan et al(2014), Thompson et al(2014)
soil subsidence	Y.M. Lee & C.S. Lee(2004), J.M. Lee et al(2006), K.I. Son(2008), K.I. Son & M.C. Kim(2010), T.U. Kang & S.H. Lee(2012), Ellis, J. Bryan et al(2014)

Categories found at Table2 and Table3 almost consist of physical indicators. But, more important thing at the evaluation of coastal inundation is to find how the area at risk would be exposed to hazard. It is possible if social and economic indicators are used to evaluate at the analysis process. Table 4 shows indicators which are used to analyze coastal inundation or flooding.

Table 4. Socioeconomic Variables about coastal inundation/flood

Variables		Author(year)
Drainage		H.H. Yoo et al(2006), K.S. Tan et al(2008), K.I. Son(2008), K.I. Son & M.C. Kim(2010), T.U Kang & S.H. Lee(2012), Lian, J. J et al(2013), Ellis, J. Bryan et al(2014)
Land Use/Cover		J.M Lee et al(2006), H.H. Yoo et al(2006), K.I. Son(2008), K.I. Son & M.C. Kim(2010), T.U Kang & S.H. Lee(2012), Wang et al(2013), Y. Gao et al(2013), Angelica Murdukhayeva et al(2013), Junior Darsan et al(2013), Ellis, J. Bryan et al(2014), Thompson et al(2014)
Etc	Tide gates	Lian, J. J et al(2013),
	Inundation depth	Wang et al(2013),
	Resilience, ecological environmental	Y. Gao et al(2013),
	Local accretion rates	Angelica Murdukhayeva et al(2013),
	Sea walls	Elisabetta Genovese & Valentin Przyluski(2013)
	Buildings	J.G. Kim et al(2009)

2.3 Brief Conclusion

Coastal disasters such as inundation and erosion are the physical phenomenon which has influenced the social and economic activities and natural system at coastal areas with large damages and losses. At this time, coastal inundation could be divided by four as cause of event. First, coastal inundation is caused by storm surge due to tropical cyclones like typhoon or hurricane. Second one is inland flood due to rainfall, third is coastal inundation caused by rainfall along with sea-level change. Lastly, inundation and flood is caused by tsunami due to earthquake and landslide. Coastal inundation or flooding caused by tsunami is not considered because Korea has not been affected by impact of tsunami. But Korea has been affected by tropical cyclones such as typhoon and rainfall every summer. So protection plan is necessary at coastal areas.

For protection from various coastal hazards in advance, it is needed to find risk and vulnerable area and also analysis or assessment method is needed. At this research, risk analysis is implemented and it is estimated by combination with probability of hazard and its consequences which means ‘degree of damage’. To implement the risk analysis, Bayesian Networks (BNs) which is kind of stochastic-statistic method is used to analyze the risk of coastal inundation. BNs is the method which estimates posterior probability using prior probability and likelihoods based no Bayes' Rule. This research collected representative indicators which could reflect complicated process of coastal area. The coastal inundation risk analysis is implemented stochastically through making the network using these indicators.

After searching the variables which are usually used to evaluate the coastal inundation, there are two characteristic variables. One is used to analyze the coastal inundation caused by storm surge due to typhoon and the other one is the variables which is used to evaluate the coastal flooding caused by rainfall. As a result, in case of the former, all of 9 variables are collected; tide, wave, wind, sea-pressure, sea level rise, storm surge, elevation, water level and water depth. In the latter, all of 8 variables are searched; precipitation, tide, wind, sea-pressure, sea level rise, storm surge, elevation and soil subsidence.

First of all, this research included two characteristic variables used in both of situations and each variable, reflected well own features, also are considered to evaluate the coastal inundation risk analysis using BNs which is kind of stochastic-statistic method as objective of the research.

3. Materials & Method

3.1 Scope

3.1.1 Spatiotemporal Scope

Coastal area is divided by the land area and the sea area according to “Coastal management law” in Korea. The land area means 1km from the shoreline and the sea area means a boundary where occurs economic activity. Spatial scope of the research contains 1km from the shoreline and dong units district connected from shoreline because of considering inundation due to rainfall and typhoon multiply.

Study site is the west coast of South Korea. In detail, the site is the coastal area which contains Incheon and Gyeonggi-do. That is because the west coast area has many low-lying land and the biggest the change of tide. Also, Incheon and Gyeonggi-do is close to Seoul and has lots of social economic activities. These areas is likely to be affected by coastal hazards such as typhoon and rainfall in the future.

And at the west coast, there is a lot of islands, so this research is not analyzed these islands without Yeongjong-do Island included Incheon international airport. Figure 7 shows the study site and study boundary.

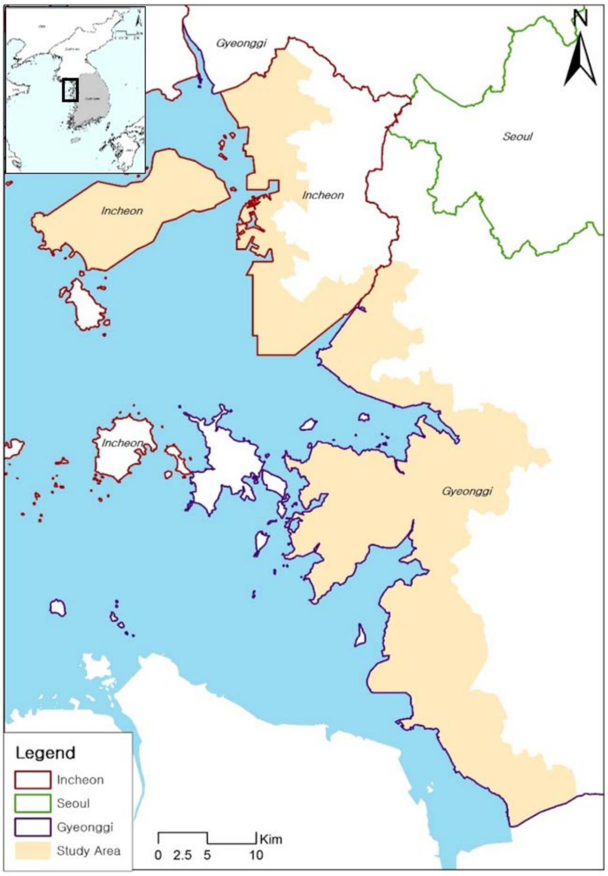


Figure 7. Study Area

3.1.2 Contextual Scope

This research only consider inundation of many coastal hazards. It is not contains Long-term event like sea-level rise. And it excludes inundation due to Tsunami of episodic events (Figure 8). Tsunami is a series of water waves caused by tremendous earthquakes, volcanic eruption and other underwater explosions. Our country has ever been affected by Tsunami.

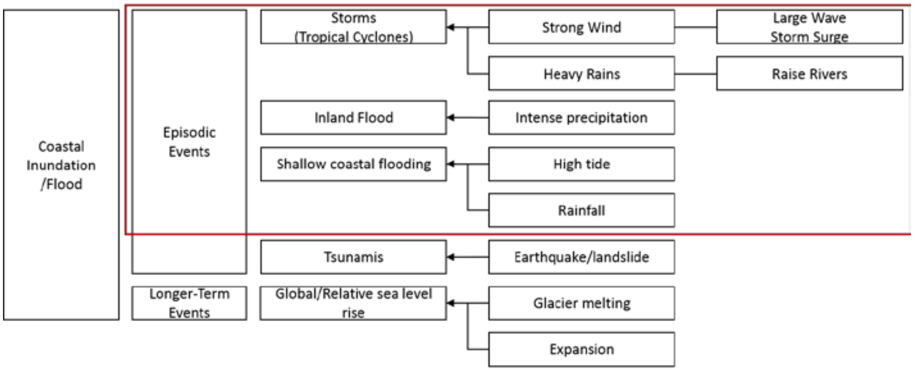


Figure 8. Contextual scope

Coastal inundation caused by episodic events could be categorized by two according to the reason of the event. First, the inundation is occurred due to tropical cyclones like typhoon. Korea has been affected by typhoon, so be damaged from inundation every summer. Second, inundation is caused by rainfall which could be divided by two events; inundation caused by rainfall in general and surface flooding along with sea-level change. So, coastal area could be considered the inundation events influenced by sea-level change.

3.1.3 Scoping

In this research, spatiotemporal and contextual scoping is applied to analyze the variables since the analysis extent is different according to the causes of coastal inundation. Inundation is largely divided into two events: typhoon and rainfall. In each inundation event, three conditions are categorized by a spatial and contextual scope. First, coastal inundation caused by a typhoon occurs by three conditions. The first situation occurs by storm surge due to a typhoon. The second situation is caused by the heavy rain of a typhoon. The third situation is surface flooding, which happens due to backward water flow along with sea level change and heavy rain. The first and third situations are considered coastal characteristics. Also, coastal inundation due to rainfall could be divided by three situations, which is different at the point of the cause of inundation, and is similar to inundation caused by a typhoon.

According to each situation, the spatial scope is different and consists of three situations (Figure 9). First, 1km from the shoreline is used to analyze the inundation caused by storm surge and sea level due to typhoon and rainfall. Thus, inundation due to surge and change of sea level is limited to the coastal areas. Second, the administrative district (dong) on the coast is used to analyze inundation caused by rainfall. A dong is the smallest district unit in Korea and is similar to a drainage district. Third, an impermeable area in a dong district on the coast is applied to analyze surface flooding, which generally happens in an impermeable area.

Also, inundation caused by typhoon and rainfall are independent events since the two events occur at different times. In the case of a typhoon, inundation caused by storm surge first arrives and then affects an area. Inundation caused by heavy rain arrives after a typhoon and results in surface flooding. In the case of inundation caused by rainfall, inundation first occurs by change of sea level and heavy precipitation events, then surface flooding. The time differences of these affects are applied with a weighed value to estimate the probability of hazard.

Table 5. Scoping for analysis

Coastal Inundation causes	Typhoon			Rainfall		
	↙	↓	↘	↙	↓	↘
Contextual	Storm Surge	Heavy Rain	Shallow Coastal Flooding	Sea level	Rainfal l	Shallow Coastal Flooding

Spatial	1km	Admini strative district	Impermeable Area	1km	Admini strative district	Impermeable Area
Temporal ↓	√					
	√	√		√	√	
	√	√	√	√	√	√

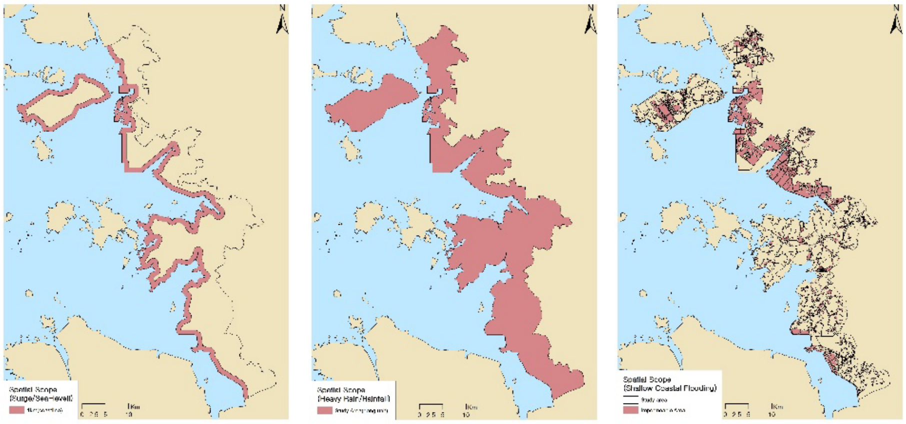


Figure 9. Three maps of spatial scope at table 5(From left to right: 1km, administrative district, impermeable area)

3.2 Dataset

3.2.1 Selection of variables

Variables used to achieve objective of the research, consist of two which are estimating the probability of hazards like typhoon and rainfall. And variables are collected by literature reviews. For reliable analysis, variables are selected as used overlapped. And socio-economic indicators are also collected and selected for estimation its consequences which means the degree of damage.

Table 6 is the list of physical variables for analysis the probability of hazard caused by typhoon. Table 7 is the list of physical variables for estimation the probability of hazard due to rainfall. And socio-economic indicators are showed at the Table 8.

Table 6. Variables of coastal inundation due to Typhoon

Title	Year	Author	physical Indicators								
			Tide	Wave	Wind	Sea -Pressure	SLR	Strom Surge	Elevation	Water Level	Water Depth
Hindcasting of storm surge at southeast coast by typhoon maemi	2005	Hiroyasu Kawai et al	tide		wind	Sea -pressure					
Risk assessment of tropical storm surges for coastal regions of China	2013	Y. Gao et al	tide								
Storm Surge in Northeastern Coastal National Parks Assessment of Inundation Risk from Sea Level Rise and	2013	Angelica Murdukhayeva et al	tide				SLR	Storm Surge	Elevation	Water level	
Flood-risk mapping for storm surge and tsunami at Cocos Bay (Manzanilla), Trinidad	2013	Junior Darsan et al		wave				Storm Surge	Elevation		
Performance and validation of a coupled parallel ADCIRC–SWAN model for THANE cyclone in the Bay of Bengal	2013	Prasad K. Bhaskaran et al	tide	wave							
Global mapping of storm surges and the assessment of coastal vulnerability	2013	G. R. Brakenridge et al	tide								
Numerical analysis of effects of tidal variations on storm surges and waves	2009	S.Y. Kim et al	tide	wave	wind						
Wave set-up in the storm surge along open coasts during Typhoon Anita	2010	S.Y.l Kim et al		wave							

A modeling study of coastal inundation induced by storm surge, sea-level rise, and subsidence in the Gulf of Mexico	2014	Zhaoqing Yang et al	tide				SLR				
Storm surge disaster risk management: the Xynthia case study in France	2013	Elisabetta Genovese & Valentin Przyluski	tide		wind	Sea -pressure					
Numerical Simulations of Storm Surge/Coastal Flooding at Mokpo Coastal Zone by MIKE21 Model	2006	S.R. Moon et al	tide		wind	Sea -pressure		Storm Surge			Water depth
Inundation Analysis of Coastal Zone due to Storm Surge	2006	D.S. Hur et al			wind	Sea -pressure		Storm Surge			Water depth
Iundation Analysis Considering Water Waves and Storm Surge in the Coastal Zone	2007	D.S. Kim et al	tide	wave	wind	Sea -pressure		Storm Surge			Water depth
Estimation of Inundation Damages of Urban area Around Haeundae Beach Induced by Super Storm Surge Using Airborne LiDAR Data	2009	J.G. Kim et al	tide		wind	Sea -pressure	SLR	Storm Surge	Elevation	Water level	
Inundation Numerical Simulation in Masan Coastal Area	2010	C.K. Kim, et al	tide		wind	Sea -pressure					
Numerical Experiments for Storm Surge Height and Coastal Inundation	2012	Y. J.J	tide		wind			Storm Surge			Water depth

Table 7. Variables of coastal inundation due to Rainfall

Title	Year	Author	physical Indicators								
			Precipitation	Tide	Wave	Wind	Sea-Pressure	SLR	Strom Surge	Elevation	soil
Joint impact of rainfall and tidal level on flood risk in a coastal city with a complex river network: a case study of Fuzhou City, China	2013	Lian, J. J et al	Precipitation	tide						Elevation	
Stochastic Event-Based Approach to Generate Concurrent Hourly Mean Sea Level Pressure and Wind Sequences for Estuarine Flood Risk Assessment	2008	Tan, K., Chiew, F., and Grayson, R				wind	sea-pressure				
Assessment of climate change impacts on flooding vulnerability for lowland management in southwestern Taiwan	2013	Wang et al	Precipitation	tide							
Sustainable Urban Drainage System Modeling for Managing Urban Surface Water Flood Risk	2014	Ellis, J. Bryan et al	Precipitation						Storm Surge	Elevation	soil
Deterministic and probabilistic flood modeling for contemporary and future coastal and inland precipitation inundation	2014	Thompson, Courtney M., Frazier, Tim G.	Precipitation			wind	sea-pressure	SLR	Storm Surge	Elevation	
Prediction of Annual Maximum Flood Levels in Coastal Catchments with Joint Probability Analysis	2004	Y.M. Lee, C.S. Lee	Precipitation	tide							soil
Inundation analysis on region of lower elevation of a new port using SWMM and UNET model	2006	J.M. Lee, S.H. Lee, S.U. Kang	Precipitation							Elevation	soil

Inundating Disaster Assessment in Coastal Areas Using Urban Flood Model	2006	Yoo H.H., W.S. Kim, S.S. Kim	Precipitation						Storm Surge	Elevation	
Runoff Estimation with Consideration of Land-Use Distribution	2008	K.I. Son								Elevation	soil
Runoff Characteristics Change of a Basin under Urbanization	2010	K.I. Son, M.C. Kim	Precipitation								soil
A Study for a Reasonable Application of the SWMM to Watershed Runoff Event Simulation	2012	T.U. Kang, , S.H Lee	Precipitation								soil

Table 8. Socioeconomic variables of coastal inundation

Title	Year	Authors	Socioeconomic Indicators					
			drainage	land use /cover	population	Culture heritage	topography	Etc
Joint impact of rainfall and tidal level on flood risk in a coastal city with a complex river network: a case study of Fuzhou City, China	2013	Lian, J. J. et al	drainage					tide gates
Stochastic Event-Based Approach to Generate Concurrent Hourly Mean Sea Level Pressure and Wind Sequences for Estuarine Flood Risk Assessment	2008	Tan, K.S. et al	drainage					
Assessment of climate change impacts on flooding vulnerability for lowland management in southwestern Taiwan	2013	Wang et al		land use				Inundation depth

Sustainable Urban Drainage System Modeling for Managing Urban Surface Water Flood Risk	2014	Ellis, J. Bryan et al	drainage	land use				
Deterministic and probabilistic flood modeling for contemporary and future coastal and inland precipitation inundation	2014	Thompson et al		land use				
Inundation analysis on region of lower elevation of a new port using SWMM and UNET model	2006	Lee, J.M. et al		land use				
Inundating Disaster Assessment in Coastal Areas Using Urban Flood Model	2006	Yoo, H.H. et al	drainage	land use				
Runoff Estimation with Consideration of Landuse Distribution	2008	Son, K.I.	drainage	land use				
Runoff Characteristics Change of a Basin under Urbanization	2010	Son, K.I. & Kim, M.C.	drainage	land use				
A Study for a Reasonable Application of the SWMM to Watershed Runoff Event Simulation	2012	Kang, T.U & Lee, S.H	drainage	land use				
Hindcasting of storm surge at southeast coast by typhoon maemi	2005	Hiroyasu Kawai et al						
Risk assessment of tropical storm surges for coastal regions of China	2013	Y. Gao et al		land use				resilience, ecological environmental
Storm Surge in Northeastern Coastal National Parks Assessment of Inundation Risk from Sea Level Rise and	2013	Angelica Murdukhayeva et al		land cover				local accretion rates

Flood-risk mapping for storm surge and tsunami at Cocos Bay (Manzanilla), Trinidad	2013	Junior Darsan et al		land use				
Storm surge disaster risk management : the Xynthia case study in France	2013	Elisabetta Genovese & Valentin Przyluski						Sea walls
Estimation of Inundation Damages of Urban area Around Haeundae Beach Induced by Super Storm Surge Using Airborne LiDAR Data	2009	Kim, J.G. et al						Buildings

From Table 6 to 8, there are indicators which are usually used at analysis. Duplicated selected and strong explanatory variables are used for estimation (Table 9). That's because each coastal inundation events shared with similar mechanism, although two events are occurred in different time. And these were used to analyze coastal inundation caused by typhoon and rainfall.

Also, storm surge developed by typhoon could be calculated by combination of tide, wave, wind set-up and pressure set-up (Figure 10). At this time, wind set-up is calculated by using wind speed, length of bay and water depth (Figure 11). Water depth is not selected, since is used to calculate the wind set-up. So, Table 10 is the list of variables selected for risk analysis lastly.

Table 9. Second selection of variables for risk analysis

<table>
<tr><th>Division</th><th>Condition</th><th>Selection of variables</th></tr>
<tr><td rowspan="2">Physical indicators</td><td>Coastal Inundation/Flood Due to Typhoon</td><td>Tide, Wave, Wind, Sea-pressure, Storm surge, Water depth + Elevation, Soil</td></tr>
<tr><td>Coastal Inundation/Flood Due to Rainfall</td><td>Precipitation, Elevation, Soil + Tide, Wave</td></tr>
<tr><td>Socioeconomic indicators</td><td>Coastal Inundation/Flood Due to Socioeconomic condition</td><td>Drainage, Land use/cover</td></tr>
</table>

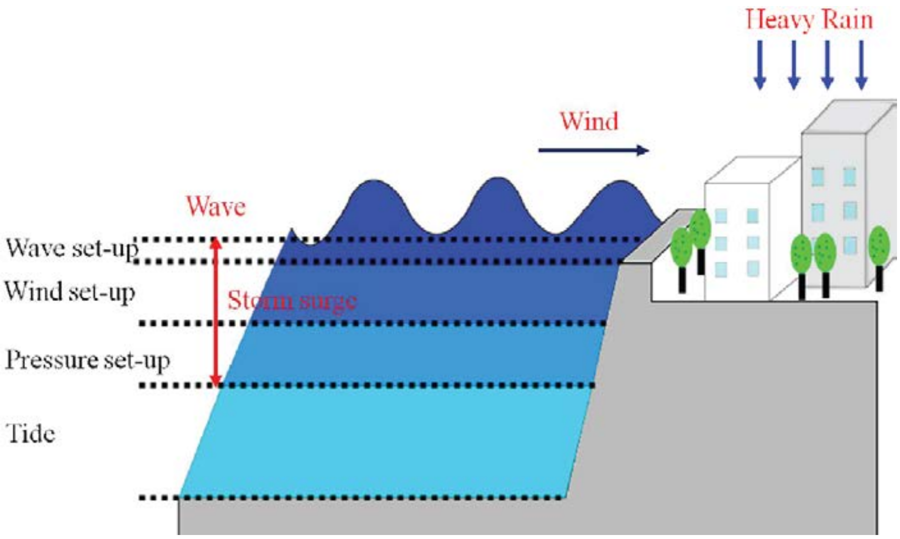


Figure 10. Description of Storm surge

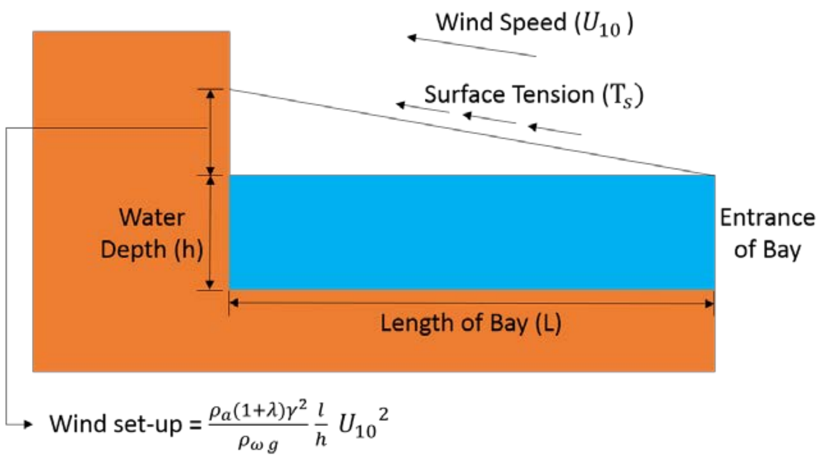


Figure 11. Description of wind set-up from storm surge

Table 10. List of variables and sources

Division	Condition	Variables	Source
Physical indicators	Coastal Inundation/Flood Due to Typhoon	Tide	KHOA
		Wave	KHOA
		Wind set-up	KHOA
		Sea-pressure set-up	KHOA
		Storm Surge	KHOA
		Elevation	KME
		Soil Depth	NAAS
		Soil Texture	NAAS
	Coastal Inundation/Flood Due to Rainfall	Tide	KHOA
		Wave	KHOA
		Sea-level	KHOA
		Precipitation	KMA
		Elevation	KME
		Soil Depth	NAAS
		Soil Texture	NAAS
Socioeconomic indicators	Coastal Inundation/Flood Due to Socioeconomic condition	Drainage length	SK
		Land use/cover	KME

Additionally, the one thing is supposed to analysis in step of estimation the probability of hazard caused by typhoon. Wind set-up and pressure set-up, used to estimate the storm surge caused by typhoon, are supposed to the strongest values that have ever effected Korea like Rusa (2003) or Maemi (2002) using wind speed, sea-pressure and precipitation at that time. As using these values, discriminated variables are tide, wave and water depth.

3.2.2 Data Collection

From the front step, Table 10 shows variables finally selected for risk analysis and sources of each variables. External variables of physical indicators are collected from KHOA (Korea Hydrographic and Oceanographic Administration) such as tide, wave, water depth, storm surge and sea-level. And precipitation data is get from KMA (Korea Meteorological Administration). Internal variables such as elevation, soil depth and soil texture are collected from KME (Korea Ministry of Environment) and NAAS (National Academy of Agricultural Science). Land Cover/Use data as socio-economic indicator is get from KMA (Korea Ministry of Environment) and drainage Length is get from SK (Statistics Korea) which provides drainage length data by district units in Korea. So, it needs to redistribute in details using population density.

It is useful to collect the data which could be collected from governments because it is helpful to consider availability and applicability of next researches. And it also helps to secure reliability of the research.

3.3 Method

3.3.1 Framework

The research method starts from the concept of risk analysis. Risk analysis is carried out through the combination of 'possibility of hazard' and the 'degree of damages' when the hazard happens as mentioned above. The possibility of hazard is called the probability of hazard, which means how a risk or hazardous event happens and is usually explained by physical indicators. The probability of hazard in this study consists of an event caused by typhoon and rainfall. A typhoon is an extreme event and rainfall is a general event in this study.

The physical variables are divided by external and internal events. In the case of a typhoon, the external variables are tide, wave, wind set-up, sea-pressure set-up and storm surge (Table 10). The Internal variables are elevation, soil depth and soil texture. In the case of rainfall, the external variables are tide, and wave and sea level, which combine the tide and wave variables. The internal variables are elevation, soil depth and soil texture, which are same as in the case of a typhoon. The remarkable difference between typhoon and rainfall is the use of variables that estimate storm surge and inundation due to rainfall.

After we collect the indicator data according, the next step is to create a network for risk analysis. The probability of each hazard such as typhoon and rainfall are estimated by Bayesian Network methodology and each calculating processes are based on Bayes' Rule. The combination of probabilities of hazards is the total probability of hazard caused by typhoon and rainfall. The combination of probabilities is used to estimate the consequences as input data or prior probability information.

The consequences estimate 'the degree of damages' when a hazard situation occurs. The consequences are calculated by using socio-economic indicators because the degree of damages could be explained by socio-economic factors in spite of the probability of a hazard calculated by physical indicators. In this research, socio-economic indicators are land use/cover and drainage length, which are selected through existing studies. Land use/cover is categorized by four dimensions: human, infrastructure, socio-economic and environment. Each dimension contains variables (Figure 12).

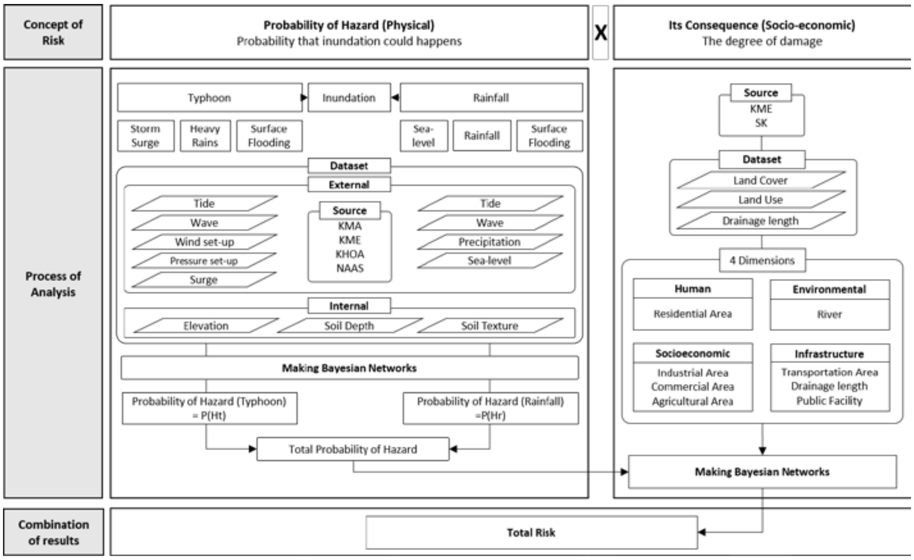


Figure 12. Framework of Method

The four dimensions are human, socio-economic, infrastructure and environment. Land use/cover contains information that is relevant to the four dimensions. The human dimension is replaced by the residential area of land use/cover and the socio-economic dimension contains industrial, commercial and agricultural area of land use/cover. The infrastructure dimension consists of public facility, transportation of land use/cover and drainage data. Finally, the environment dimension contains forest, grass land and rivers in land use/cover data. Nine indicators are divided by four dimensions and each factor is applied in a network for an estimation of risk analysis.

3.3.2 Method in details

Method is explained in details in this section. This is about how to draw the result through process of analysis. As mentioned, concept of methodology is “risk analysis” which was carried out through the combination of ‘probability of hazard’ and the ‘level of damages’. Probability of hazard would be estimated by physical indicators and ‘degree of damages’ is calculated by socio-economic indicators.

Probability of hazard could be divided into two parts according to causes which comes from typhoon and rainfall. First of all, inundation due to typhoon has three situations which are risk of storm surge and heavy rain and surface flooding. Probability of inundation due to storm surge is estimated by combination with tide, wave, wind set-up and pressure set-up along with elevation. Probability of inundation caused by heavy rain due to typhoon is estimated by three variables which are elevation, soil depth and soil texture. These variables affect the risk of inundation due to rainfall as ever known. So, lower land is more vulnerable because water flows from up to down and permeability and moisture content of soil is also crucial factors of inundation according to its temper. Lastly, surface flooding is occurred by earlier two events which are storm surge and heavy rain. It means that it is happened when heavy rain comes and could not be emitted to the sea along with storm surge. It is occurred easier in impermeability areas than the other areas.

In the other hand, inundation due to rainfall could be explained similar to inundation caused by typhoon, since the situations of inundations are similar. First of all, inundation due to sea-level could rise in general situation and it is could be estimate by combination of tide, wave and elevation data. And low-lying land inundation is estimated by using precipitation, elevation, soil texture and soil depth data. Lastly, surface flooding is occurred by using rainfall and sea-level. It is different with the former.

The two situations of probability of hazard are estimated by using Bayesian Network based on Bayes' Rule with indicators and variables as nodes which are mentioned at section 2. And the combination of two probabilities is total probability of hazard which would be spatially estimated.

It is used to calculate each degree of damages for risk analysis using Bayesian Network with socio-economic indicators which are Land use/cover data and drainage length. At this time, the socio-economic indicators are categorized to four dimensions; human, socio-economic, infrastructure and environment. Each factors also contains variables according to land use/cover. For example, human factors is calculated by residential area. Using 9 variables, it would be made a network for calculating the risk through the Bayesian Network.

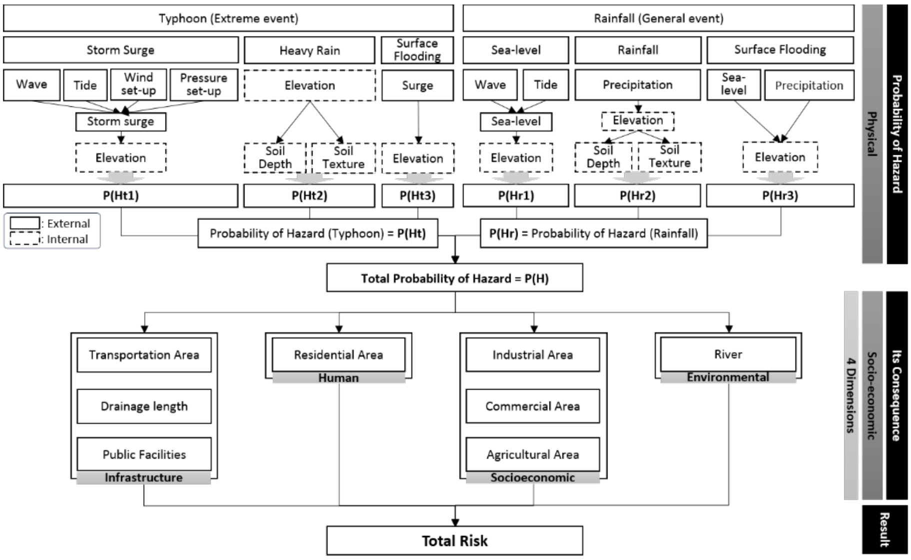


Figure 13. Method in details

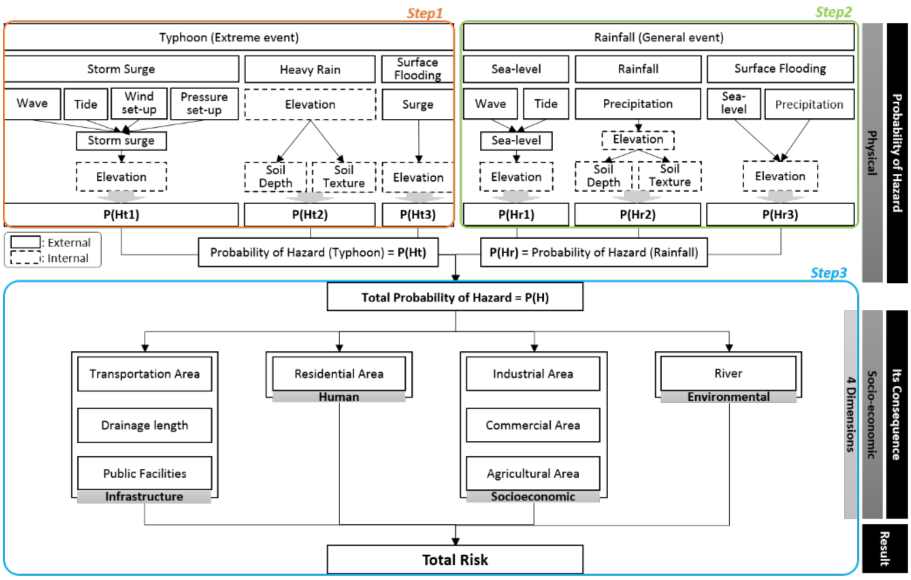


Figure 14. Steps of Analysis

4. Results

4.1 Step1

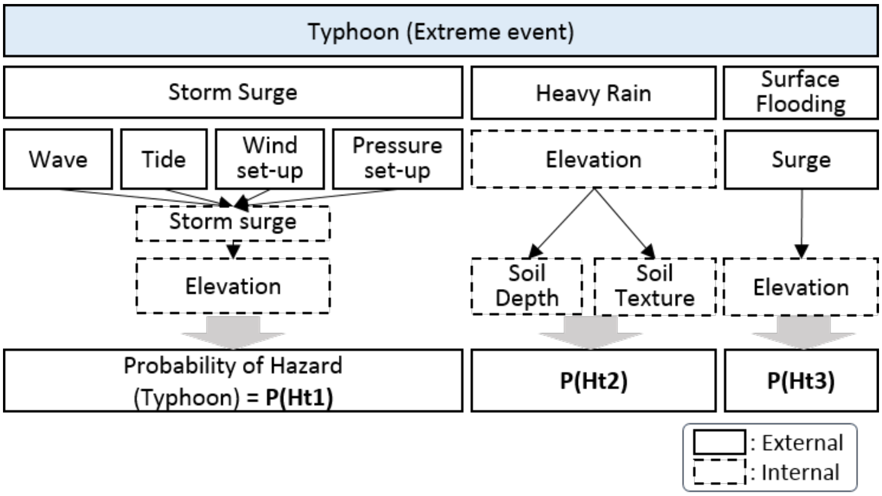


Figure 15. Step1 estimated the probability of hazard caused by Typhoon

Table 11. Abbreviation and Unit of Variables at Step1

Division	Condition	Variables	Abbreviation	Unit	Source
Physical indicators	Coastal Inundation/Flood Due to Typhoon	Tide	T	Meter	KHOA
		Wave set-up	Wa	Meter	KHOA
		Wind set-up	Wi	Meter	KHOA
		Sea-pressure set-up	SP	hpa	KHOA
		Storm Surge	S	Meter	KHOA
		Elevation	E	Meter	KME

		Soil Depth	SD	cm	NASS
		Soil Texture	ST	#	NASS

Step1 estimates the probability of hazard caused by a typhoon. The probability of coastal inundation caused by a typhoon is estimated by dividing the three situations (Figure 15). P(Ht1) is the probability of inundation hazard due to storm surge caused by a typhoon. P(Ht2) is the probability of inundation hazard due to heavy rain. P(Ht3) is the probability of surface flooding caused by the overflow of drainage.

Before the analysis of Step 1, the most impressive typhoon that ever affected Korea is considered (e.g., Maemi, 2002; Rusa, 2003). In detail, the maximum wind speed, maximum precipitation and minimum sea-pressure are considered at that time. The fixed variables used to find other relative data are also considered.

First, P(Ht1) is evaluated by using six variables: tide, wave, wind speed, sea-pressure, storm surge and elevation. By using these six variables, the network is created to analyze the probability of hazard using the Bayesian estimation method. The spatial scope is 1km from the shoreline according to the ‘Coastal management law’ in Korea. Storm surge is calculated by tide, wave, wind set-up and sea-pressure set-up. The maximum wind speed and minimum sea-pressure are used to calculate the wind set-up and the sea-pressure set-up, respectively. Wind set-up is estimated by using water depth, length of bay and wind speed. At this time, data for wind speed and length of bay are fixed. Thus, wind set-up is different according to water depth. Water depth is an inverse proportion to wind set-up. So, the lower the water depth, the higher the wind set up. Sea-pressure is also fixed data and sea-pressure set-up is data that is estimated by using the difference of air pressure (Figure 16). The unit of sea-pressure set-up is in centimeters. For example, if the sea-pressure of a typhoon is 960hpa and average pressure of air is 1013hpa, sea-pressure set-up is 53cm (1013hpa-960hpa). When the unit of sea-pressure is used in the actual analysis, the unit is used in terms of the meter units. The elevation data is the most important piece of information at this step since the results of Step 1 are different according to the elevation.

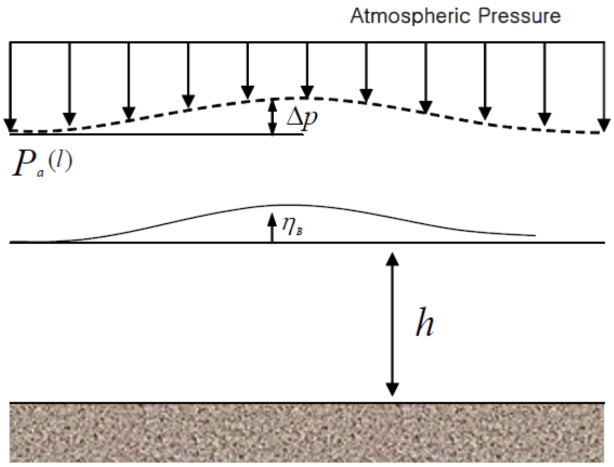


Figure 16. Description of sea-pressure set-up

Storm surge is estimated by using tide, wave, wind set-up and sea-pressure set-up and storm surge affects the elevation. The network is created by these relationships of variables. The probability of hazard caused by storm surge due to a typhoon is called P(Ht1) in this study and is calculated by using the Bayesian estimation method. The calculation process of P(Ht1) is shown in Equation 2 where P(Wi), P(Wa), P(T), P(E) and P(S) are the prior probabilities and P(S|E) and P(Wi, Wa, T, SP|E) are likelihoods based on Bayes' Rule. The posterior probability is estimated by combining prior probabilities and likelihoods and is the result of P(Ht1).

$$
\begin{aligned}
P(Ht1) &= P(E|S) \\
&= \frac{P(E) \times P(S|E)}{P(S)} \\
&= \frac{P(E) \times P(S|E)}{P(S|Wi, Wa, T, SP)} \\
&= \frac{P(Wi) \times P(Wa) \times P(T) \times P(SP) \times P(E) \times P(S|E)}{P(S) \times P(Wi, Wa, T, SP|S)} \\
&= \frac{P(Wi) \times P(Wa) \times P(T) \times P(E) \times P(S|E)}{P(S) \times P(Wi, Wa, T, SP|S)}
\end{aligned} \tag{2}
$$

Now, we explain how to make the prior probabilities of each variable. First, the prior probability data should fill in each cell as a different value. For this, the four variables are tide, wave, wind set-up and sea-pressure set-up, which are estimated to construct the prior probability such as Equation (3).

$$
\begin{aligned}
&Prior\ probability\ of\ a\ variable \\
&\qquad = \frac{Height\ of\ variable\ - Elevation}{Height\ of\ variable}
\end{aligned} \tag{3}
$$

※ Height of variable: maximum data

The prior probability of elevation is classified (Table 12). The cumulated ratio of cell counts for each class is the prior probability of elevation. The more the class increases, the more the area is at risk. The classification standard is based on the height of the variables that are used at the estimation of developing the prior probabilities of tide, wave, wind set-up and sea-pressure set-up.

The prior probability of elevation derived from the classification is shown in Table 13. The prior probability of elevation also shows the likelihoods among variables. The likelihoods mean how a variable influences other variables. In this study, likelihoods are indicated by the relationship between the four variables and elevation and are estimated by where the maximum data of a variable is located at a certain range of elevation. Figure 17 shows the prior probabilities of five variables, which are tide, wave, wind set-up, surge and elevation.

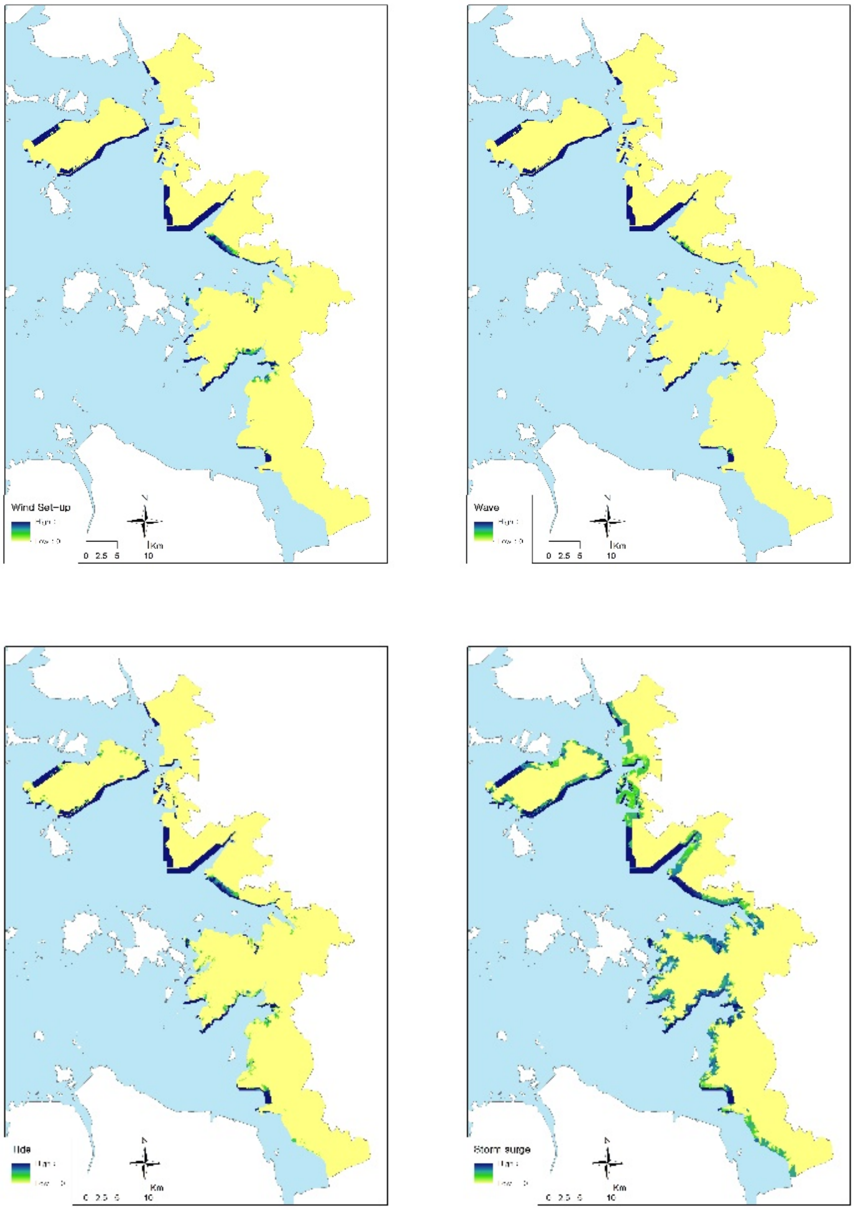
Table 12. Classification of elevation

	1	2	3	4	5	6
Elevation(m)	77.9 – 153.45	70.50 – 77.9	4.89 – 70.50	2.69 – 4.89	0.59 – 2.69	0 – 0.59

Table 13. Prior probabilities of elevation and Likelihoods of each variables

	1	2	3	4	5	6
Elevation	1%	1%	63%	77%	81%	100%
Likelihood	Wind set-up		→ elevation		91%	

	Tide Wave Sea-Pressure Storm Surge		6% 3% 1% 51%



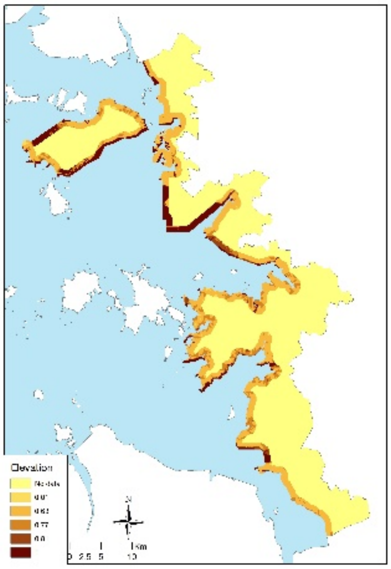


Figure 17. Prior probabilities of variables; wind set-up, tide, wave, surge, elevation

The Next process for Step 1 is the estimation of P(Ht2), which is the calculation of probability of coastal inundation due to rainfall. P(Ht2) is calculated as Equation 4 based on Bayes' Rule. Unlike Equation 2, P(Ht2) is calculated by using internal variables such as elevation and soil information. The spatial scope of analysis for P(Ht2) are dong units that are close to the shoreline. In this process, external variables such as precipitation, wind speed, wave and tide are not used because the external variables are supposed to be fixed. Thus, elevation, soil texture and soil depth are selected to evaluate the probability of coastal inundation due to rainfall.

The process of P(Ht2) is similar to P(Ht1). The three variables that are used to evaluate P(Ht2) are classified by a series of standards and the prior probabilities of each variable are determined and calculated by Bayes' Rule. Table 14 shows the classification of three variables. Soil texture and soil depth are classified by using water permeability and water content capability of soil, respectively. Table 15 shows the prior probabilities of each variable and likelihood. Soil texture and soil depth both influenced elevation and these variables are likelihoods. The likelihoods of the two variables are estimated by using the ratio of cells, which are the counted cells of four classes corresponding to the elevation range. Figure 18 shows the prior probabilities of elevation, soil depth and soil texture.

$$\begin{aligned} P(Ht2) &= \frac{P(\mathrm{SD}|\mathrm{E}) + P(\mathrm{ST}|\mathrm{E})}{2} \\ &= \left(\frac{P(SD) \times P(E|SD)}{P(E)} + \frac{P(ST) \times P(E|ST)}{P(E)}\right) \times 0.5 \end{aligned} \quad (4)$$

Table 14. Classification of variables

	1	2	3	4	5	6
Elevation(m)	77.9 – 292.9	70.50 – 77.9	4.89 – 70.50	2.69 – 4.89	0.59 – 2.69	0 – 0.59
Soil Depth(cm)	>100	50-100	20-50	<20		
Soil Texture	Coarse	Sand	Silt	Clay		

Table 125. Prior probabilities of variables and Likelihoods

	1	2	3	4	5	6
Elevation	3%	4%	77%	90%	92%	100%
Soil Depth	22%	57%	63%	100%		
Soil Texture	10%	65%	99%	100%		
Likelihood	Soil Depth Soil Texture		→ elevation		25% 75%	

P(Ht3) is the estimation of the probability of surface flooding caused by rainfall and sea level change. P(Ht3) is calculated using Equation 5. The spatial scope of P(Ht3) is an impermeable area in dong units that are close to the shoreline because surface flooding occurs usually in impermeable areas. In this process, the change of sea level is an important variable. Thus, only storm surge and elevation are used to evaluate P(Ht3).

As mentioned, P(Ht3) is calculated by using Bayesian method through the classification and prior probabilities of variables. Table 16 shows the classification of variables. Table 17 shows the prior probability and likelihoods of variables. Figure 19 shows the probability of surge and elevation.

As a result of Step 1, P(Ht1), P(Ht2) and P(Ht3) are shown in Figure 20. The total probability of a coastal hazard caused by a typhoon is called P(H) and is estimated by the combination of P(Ht1), P(Ht2) and P(Ht3) in Step 1. The P(Ht1), P(Ht2) and P(Ht3) results are weighted according to the difference of temporal impact at scoping. At the Bayesian Networks (BNs), the prior probability and the results are presented as a probability of 0 to 1.

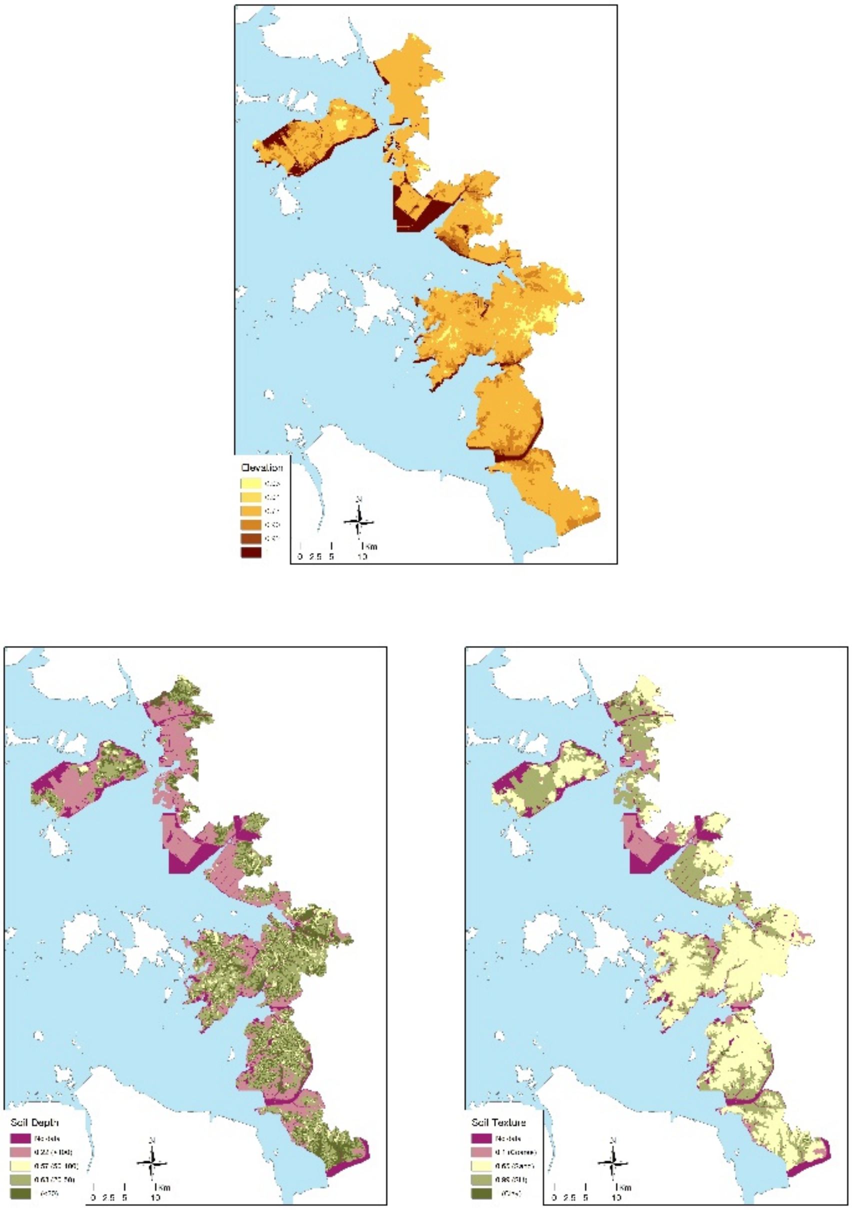


Figure 18. Prior probability of variables; elevation, soil depth, soil texture

$$P(Ht3) = P(E|S) = \frac{P(E) \times P(S|E)}{P(S)} \qquad (5)$$

Table 136. Classification of variables

	1	2	3	4	5
Elevation(m)	10.09 – 175.02	4.89 – 10.09	2.69 – 4.89	0.59 – 2.69	0 – 0.59

Table 147. Prior probabilities of variables and Likelihoods

	1	2	3	4	5
Elevation	28%	79%	90%	93%	100%
Likelihood	surge		→ elevation	6%	

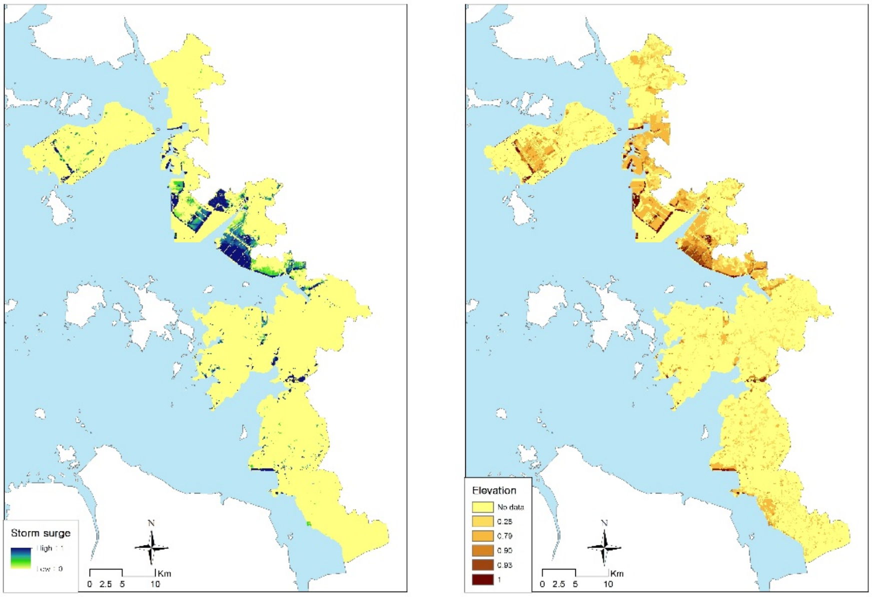


Figure 19. Prior probability of variables; surge, elevation

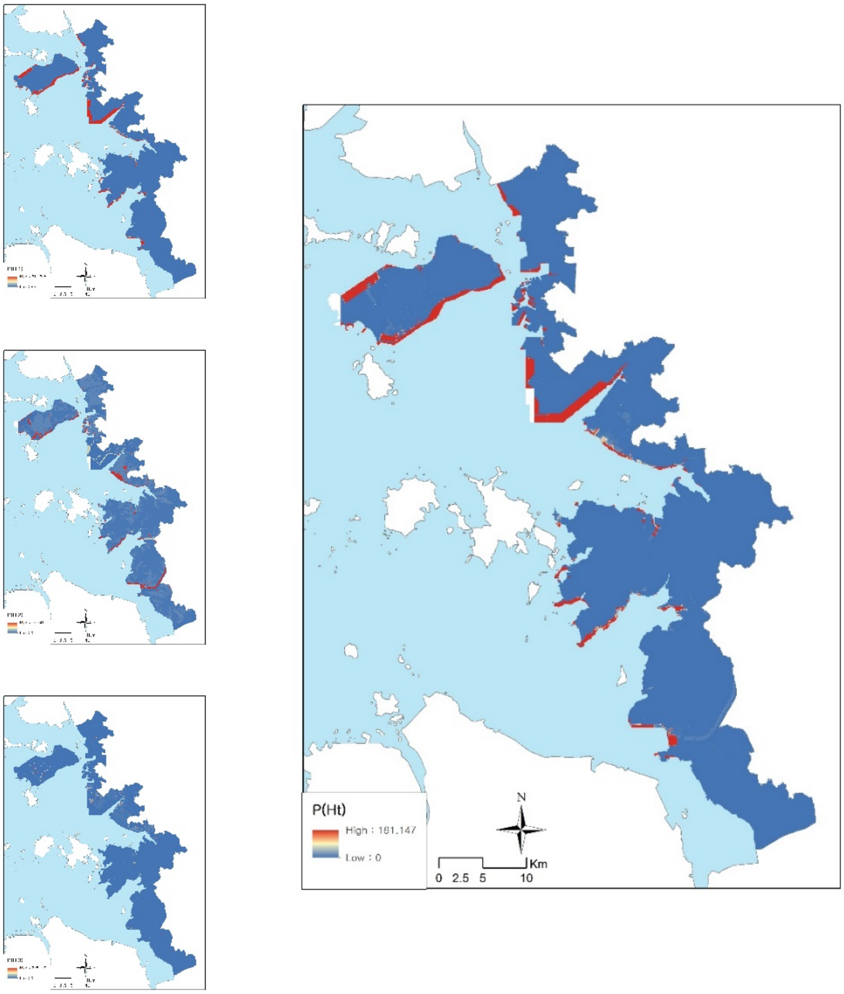


Figure 20. Results of each and results of step1

4.2 Step2

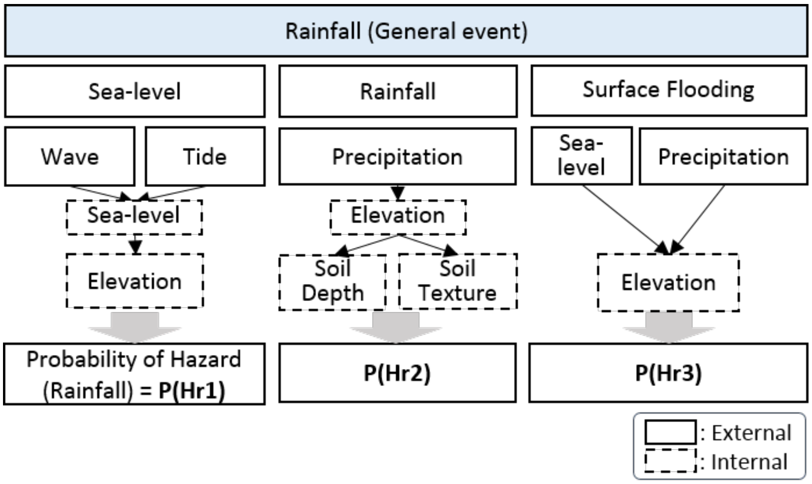


Figure 21. Step2 estimated the probability of hazard in case of Rainfall

Table 158. Abbreviation and Unit of Variables used in Step2

Division	Condition	Variables	Abbreviation	Unit	Source
Physical indicators	Coastal Inundation/Flood Due to Rainfall	Tide	T	Meter	KHOA
		Wave	Wa	Meter	KHOA
		Precipitation	P	mm	KMA
		Sea-level	SL	Meter	KHOA
		Elevation	E	Meter	KME
		Soil Depth	SD	cm	NASS
		Soil Texture	ST	#	NASS

Step 2 is the process that evaluates the probability of coastal inundation caused by rainfall. As mentioned in Step 1, Step 2 is also divided by three situations and each situation could be estimated to obtain its own probability of coastal inundation. The biggest difference of Step 1 and Step 2 is that Step 2 contains precipitation and sea level data. Otherwise, Step 1 uses surge data. Other conditions of Step 2 are similar to Step1 except for these differences.

Step 2 is categorized by three situations, which are inundation caused by sea level, flooding caused by rainfall and surface flooding due to rainfall and sea level change. All of the seven variables are selected and the network is created to analyze the probability of coastal inundation using the Bayesian method from these variables.

First, coastal inundation caused by sea level change is estimated using Equation 6 according to Bayes' Rule. This process is called P(Hr1) and uses four variables, which are tide, wave, sea level and elevation. Sea level is calculated by using tide and wave data and the result of P(Hr1) can be different according to sea level. The spatial scope is the same as P(Ht1)'. Table 19 and Table 20 show the classification of elevation and prior probability for each elevation, which are illustrated as a map in Figure 22. Similar to Step 1, tide and wave are used.

$$\begin{aligned}
P(Hr1) = P(E|SL) &= \frac{P(E) \times P(SL|E)}{P(SL)} \\
&= \frac{P(E) \times P(SL|E)}{P(SL|Wa,T)} \\
&= \frac{P(E) \times P(SL|E)}{\frac{P(SL) \times P(Wa,T|SL)}{P(Wa) \times P(T)}} \\
&= \frac{P(Wa) \times P(T) \times P(E) \times P(SL|E)}{P(SL) \times P(Wa,T|SL)}
\end{aligned} \tag{6}$$

Table 169. Classification of variables

	1	2	3	4
Elevation(m)	7.49 – 153.45	4.89 – 7.49	2.69 – 4.89	0– 2.69

Table 20. Prior probabilities of variables and Likelihoods

	1	2	3	4
Elevation	33%	63%	77%	100%
Likelihood	Tide Wave Sea-level	→ elevation	65% 36% 5%	

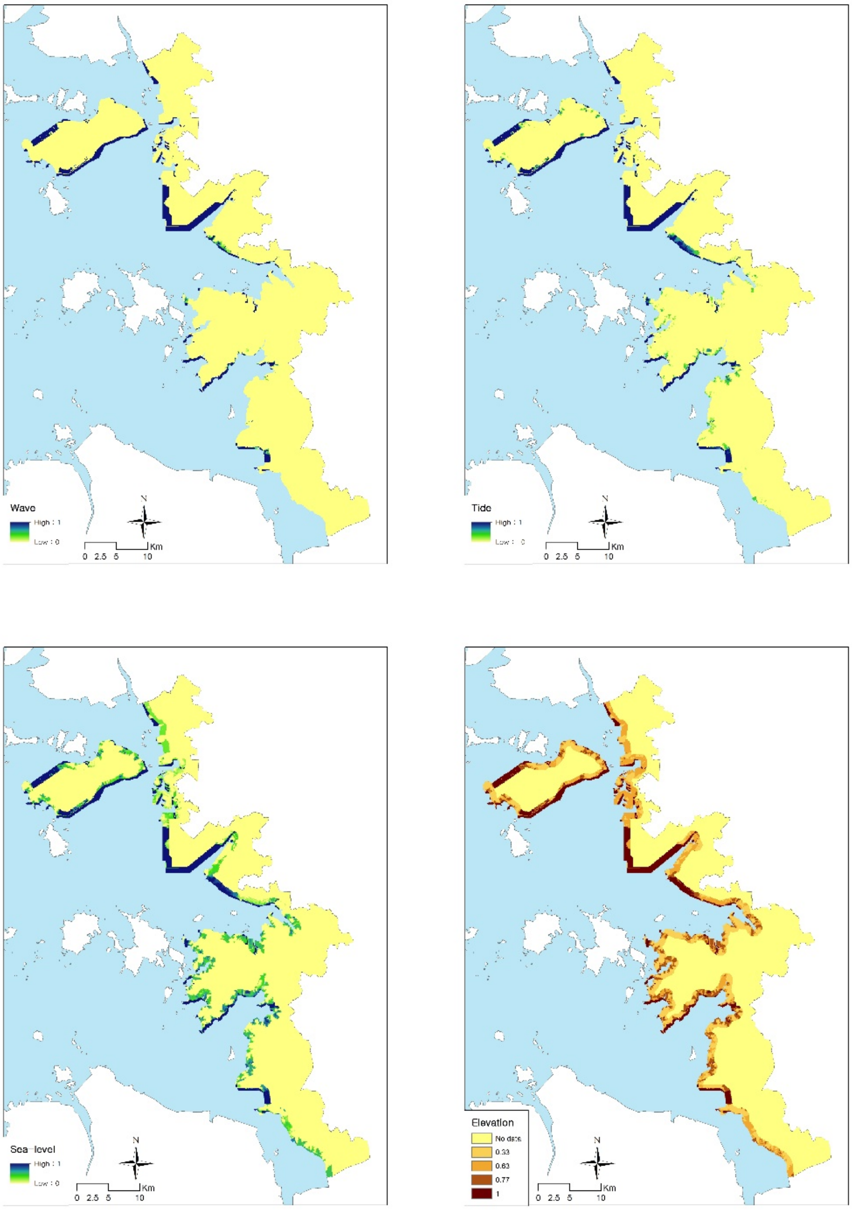


Figure 22. Prior probability of variables; tide, wave, sea-level, elevation

Next, P(Hr2) means that the probability of coastal inundation caused by rainfall is estimated. Equation 7 shows the calculation. The important concept is that P(Hr2) uses precipitation data, which is collected by the Korea Meteorological Administration. However, other conditions are similar to the process of Step 1. Table 21 is a classification of variables, which are precipitation, elevation, and soil texture and soil depth. According to the classification of variables, the prior probabilities for each variable and likelihood are shown in Table 22 and illustrated as a map in Figure 23. The precipitation data is classified by using the probability frequency of precipitation. The classification is defined by probable rainfall according to the return period using Table 23.

$$
\begin{aligned}
P(Hr2) &= \left(P(\mathrm{SD|E}) + P(\mathrm{ST|E})\right) \times 0.5 \\
&= \left(\frac{P(SD) \times P(E|SD)}{P(E|P)} + \frac{P(ST) \times P(E|ST)}{P(E|P)}\right) \times 0.5 \\
&= \left(\frac{P(P) \times P(SD) \times P(E|SD)}{P(E) \times P(P|E)}\right. \\
&\qquad \left. + \frac{P(P) \times P(ST) \times P(E|ST)}{P(E) \times P(P|E)}\right) \times 0.5
\end{aligned}
\tag{7}
$$

Table 21. Classification of variables

	1	2	3	4	5	6
Precipitation(mm)	< 293.4	293.4-318.9	318.9-344.4	344.4-357.2	357.2-392.2	392.2 >
Elevation(m)	7.49 – 292.9	4.89 – 7.49	2.69 – 4.89	0– 2.69		
Soil Depth(cm)	>100	50-100	20-50	<20		
Soil Texture	coarse	sand	silt	clay		

Table 22. Prior probabilities of variables and Likelihoods

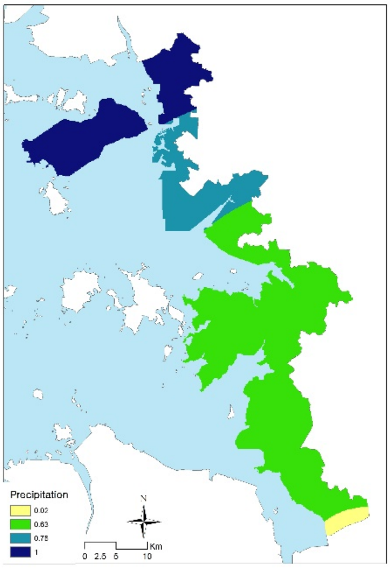
	1	2	3	4	5	6
precipitation	0%	2%	63%	78%	100%	100%
Elevation	53%	77%	90%	100%		
Soil Depth	22%	57%	63%	100%		
Soil Texture	10%	65%	99%	100%		
Likelihoods	Soil Depth Soil Texture		→ elevation		25% 75%	

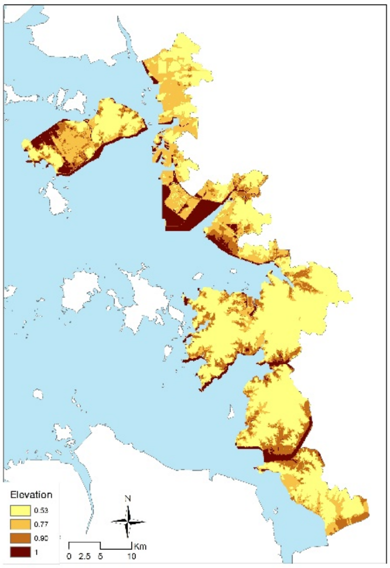
Table 2173. The national average probable rainfall ('50 frequency) and the ratio of probable rainfall according to return period (MCT, 2000)

Division	Rainfall duration								
	60’	120’	180’	240’	360’	720’	1080’	1440’	2880’
Average probable	74.1	103.9	125.3	142.2	171.1	233.7	80.5	318.9	434.4

rainfall (mm)									

Division	Return period							
	10y	20y	30y	50y	80y	100y	150y	200y
Ratio of probable rainfall (%)	0.73	0.85	0.92	1.00	1.08	1.12	1.18	1.23





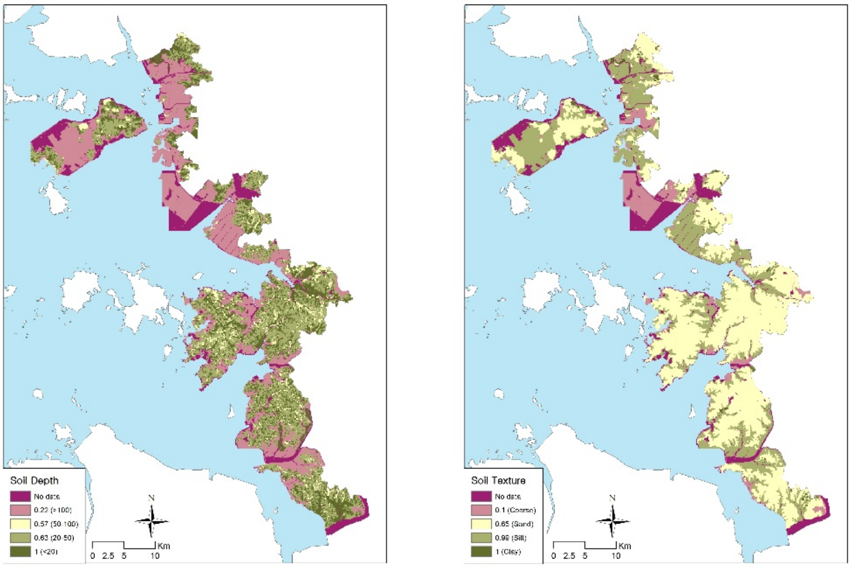


Figure 23. Prior probability of variables; precipitation, elevation, soil depth, soil texture

P(Hr3) is calculated by using precipitation, sea level and elevation. Equation 8 shows the calculation process. Otherwise, the process of P(Ht3) uses the additional precipitation data. Table 24 shows the classification standard of variables and Table 25 shows the prior probabilities of variables. Similar to Figure 24, P(Hr3) is also illustrated as a map.

$$P(Hr3) = P(E|SL, P) = \frac{P(E) \times P(SL, P|E)}{P(SL) \times P(P)} \qquad (8)$$

Table 184. Classification of variables

	1	2	3	4	5	6
Precipitation(mm)	< 293.4	293.4-318.9	318.9-344.4	344.4-357.2	357.2-392.2	392.2 >
Elevation(m)	7.49 – 175.02	4.89 – 7.49	2.69 – 4.89	0– 2.69		

Table 195. Prior probabilities of variables and Likelihoods

	1	2	3	4	5	6
Precipitation	0%	0%	48%	80%	100%	100%
Elevation	42%	83%	95%	100%		
Likelihoods	Sea-level		→ elevation		4%	

Thus, total probability of coastal inundation caused by rainfall, P(Hr), results from the combination of P(Hr1), P(Hr2) and P(Hr3) (Figure 25). The values are presented from 0 to 1, according to the Bayesian probabilistic method.

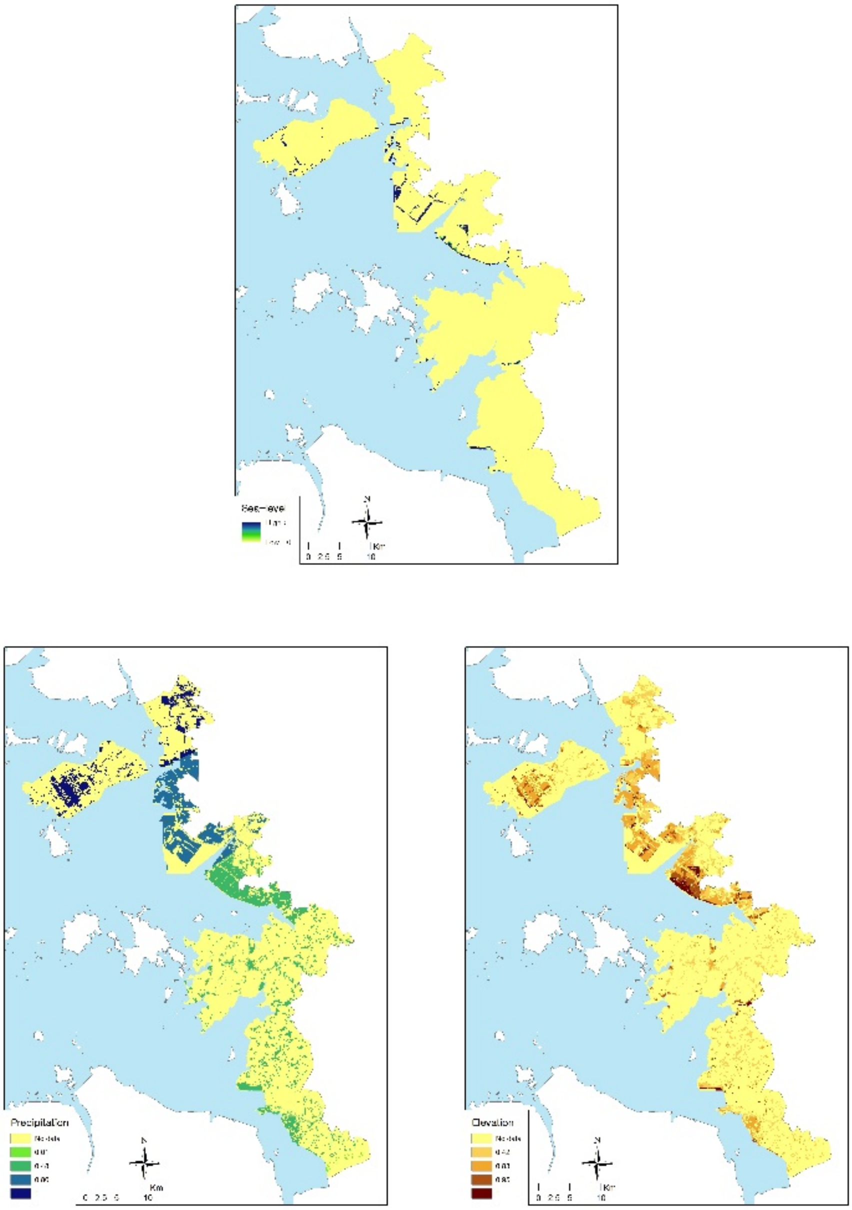


Figure 24. Prior probability of variables; sea-level, precipitation, elevation

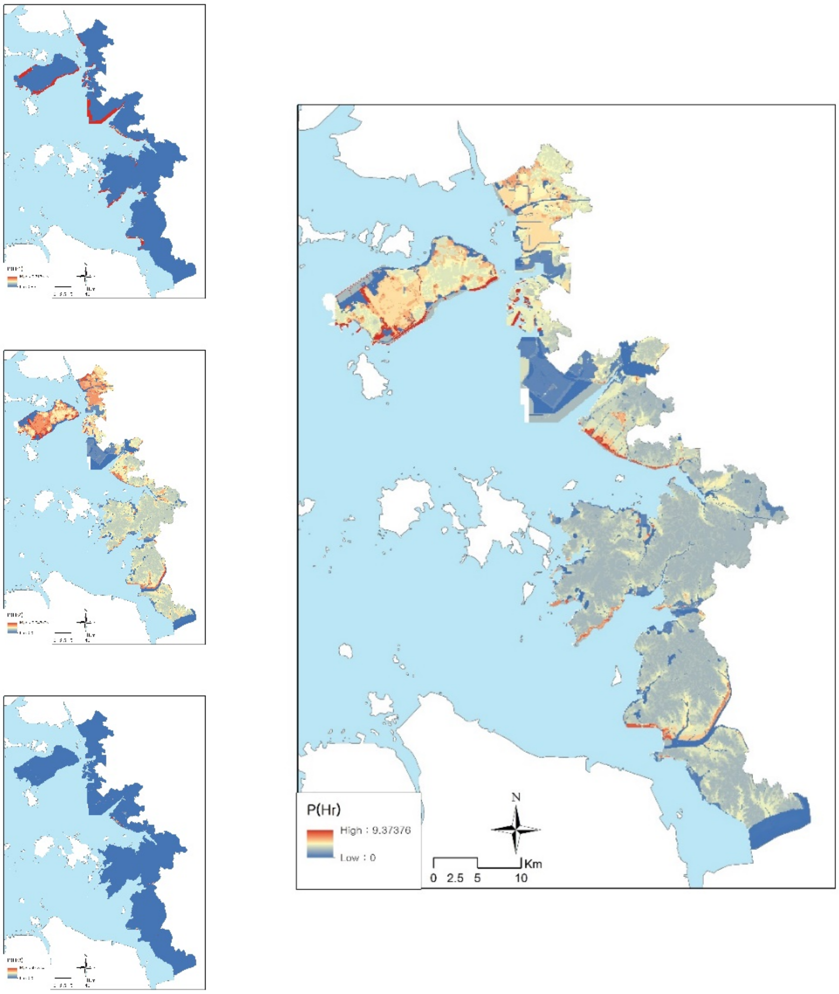


Figure 25. Results of each and results of step2

As a result, P(Ht) and P(Hr) from Steps 1 and 2 are estimated and the combination with the two results is the total probability of coastal inundation, which is called P(H) (Figure 26). We can now know the probability of coastal inundation caused by typhoon and rainfall in a year. We can also evaluate the total risk of Step 3, which uses socio-economic indicators as input data.

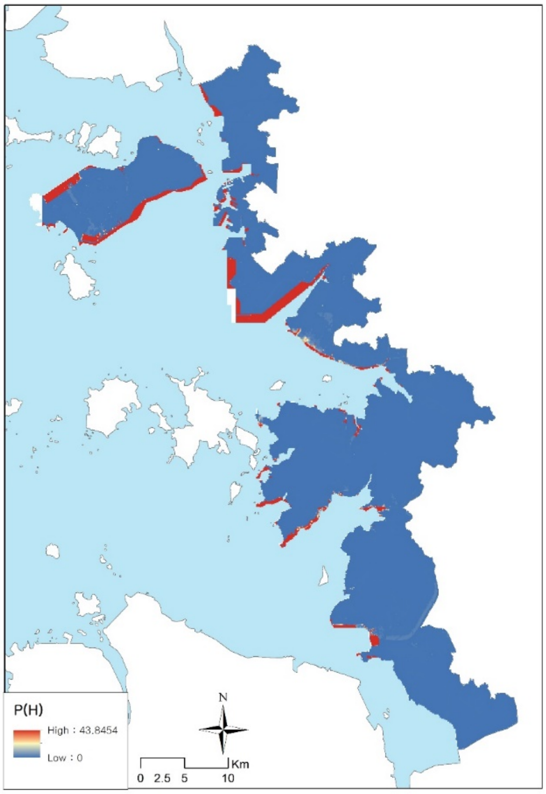


Figure 26. Total probability of coastal inundation

4.3 Step3

Step 3 was the process called ‘estimating the degree of damage’ using socio-economic indicators. As explained, socio-economic indicators were divided by four dimensions; human, socio-economic, infrastructure and environment. Each dimension contained variables that represented their own dimension. These were classified by land use or land cover data. Table 26 showed the variables in Step 3.

The network was created by using the data in Step 3 (Figure 27). The total probability of coastal inundation was applied as input data to estimate the total risk and affected all nine socio-economic variables. After creating the network, total risk was evaluated, which were the combinations of each dimension. Equations 9-12 showed the calculation processes for each dimension.

Table 206. Abbreviation of Variables in Step3

Dimension	Abbreviation	Land Use/Cover	Abbreviation
Human	Hu	Residential Area	Re
Socio-economic	Se	Industrial Area	I
		Commercial Area	C
		Agricultural Area	A
Infrastructure	In	Transportation Area	T

		Drainage Length	D
		Public Facility	P
Environment	En	River	Ri

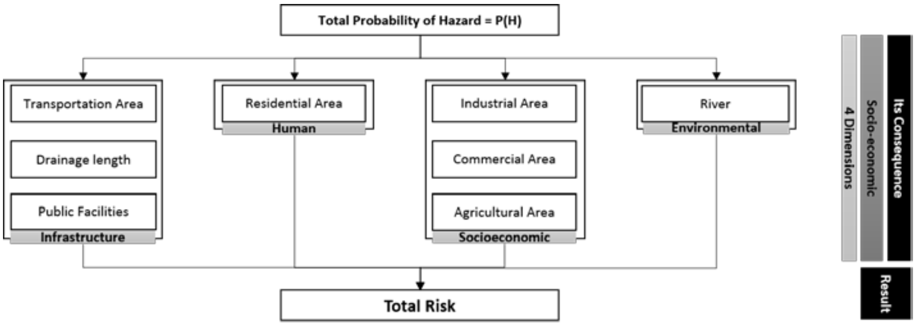


Figure 27. Bayesian network for estimating risk of four dimensions.

$$P(Hu|H) = \frac{P(Hu) \times P(H|Hu)}{P(H)} \tag{9}$$

$$P(In|H) = \frac{P(In) \times P(H|In)}{P(H)} \tag{10}$$

$$P(SE|H) = \frac{P(SE) \times P(H|SE)}{P(H)} \tag{11}$$

$$P(En|H) = \frac{P(En) \times P(H|En)}{P(H)} \tag{12}$$

The risk for each dimension is calculated by the Bayesian method from Equations 9-12. The prior probabilities of each indicator are calculated by the ratio of the residential area or land cover/use information occupied in a cell (100*100)(Figure 28). If the residential area occupies 5,000 m^2 in a cell (100*100), the prior probability of the human dimension is 0.5 (50%). Thus, Figure 29 shows the nine indicators developed by these methods.

The likelihoods are the degree of impact that the nine variables affect the socio-economic indicator. The likelihoods are based on the ratio of damage losses (Table 27).

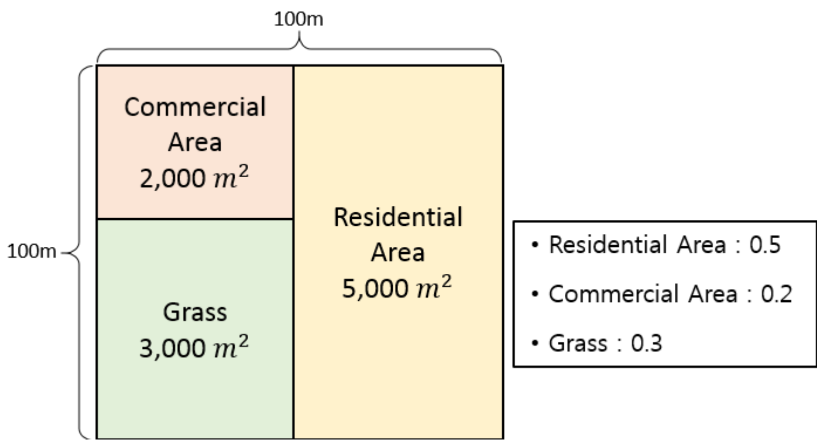


Figure 28. An example of estimating probability of each socio-economic indicators

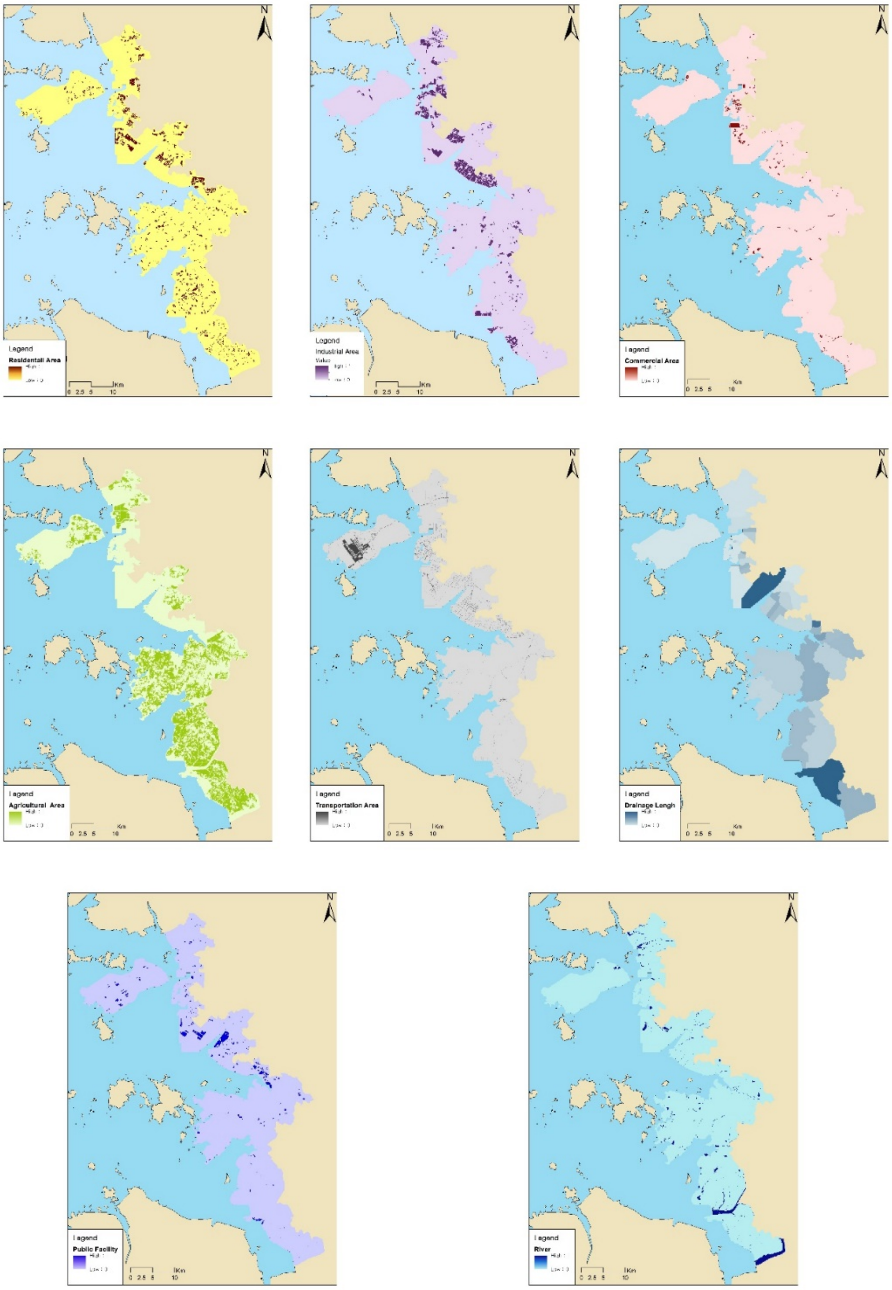


Figure 29. Prior probability of socioeconomic indicators

Table 217. Damage losses of socio-economic indicators and the ratio (NEMA, 2004-2013)

Dimension	Land Use/Cover	Damage loss (₩)		Ratio (%)		Ratio in details (%)
Human	Residential Area	38,883,000		13.8%		100%
Socio-Economic	Industrial Area	66,528,942	11,546,410	23.6%	4.1%	17%
	Commercial Area		25,384,168		9.0%	38%
	Agriculture & Fishery		29,598,364		10.5%	45%
Infrastructure	Transportation	131,064,550	12,172,959	38.2%	4.3%	9%
	Drainage		2,860,215		1.0%	2%
	Public Facility		116,031,376		32.9%	89%
Environment	River	69,169,897	45,943,370	24.5%	16.3%	100%

※ Damage loss: damage loss for past 10 years (2004-2013) according to causes

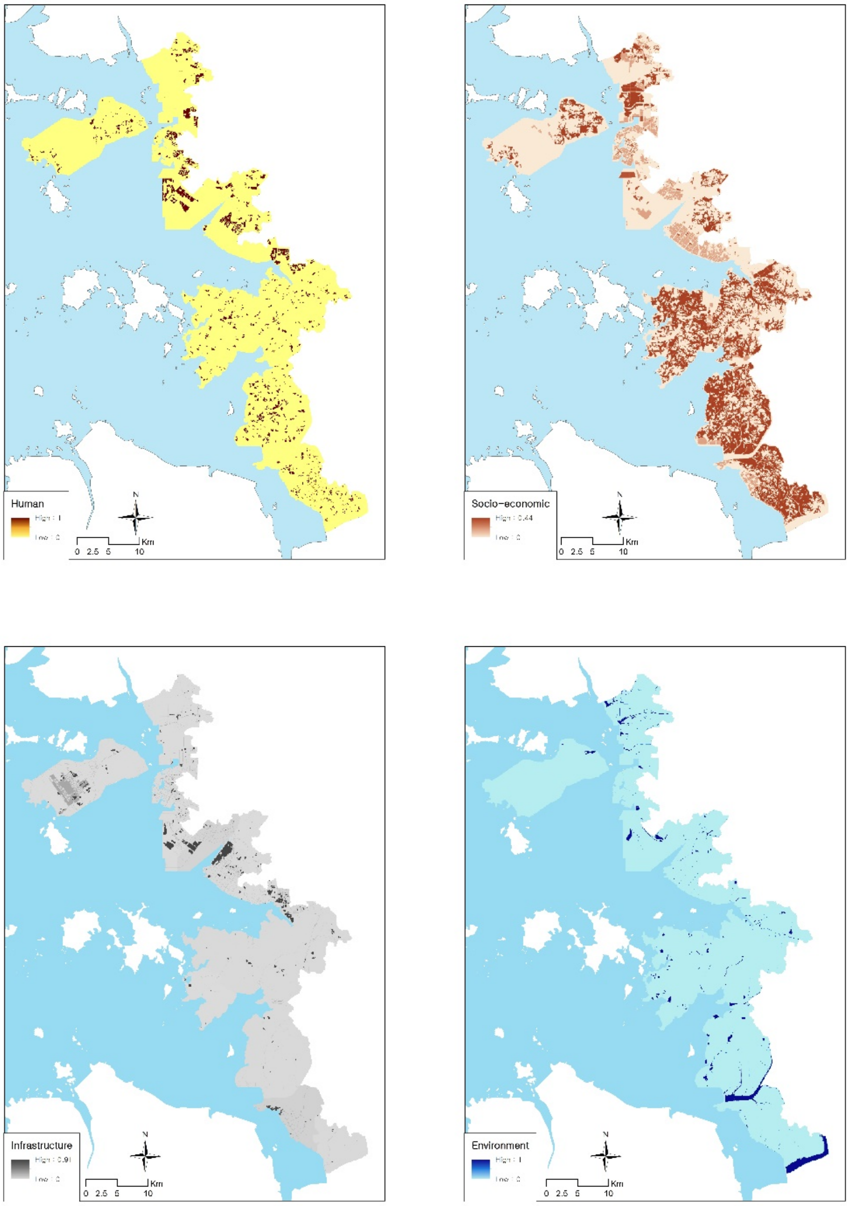


Figure 30. Prior probability of four dimensions using prior probability of socio-economic indicators

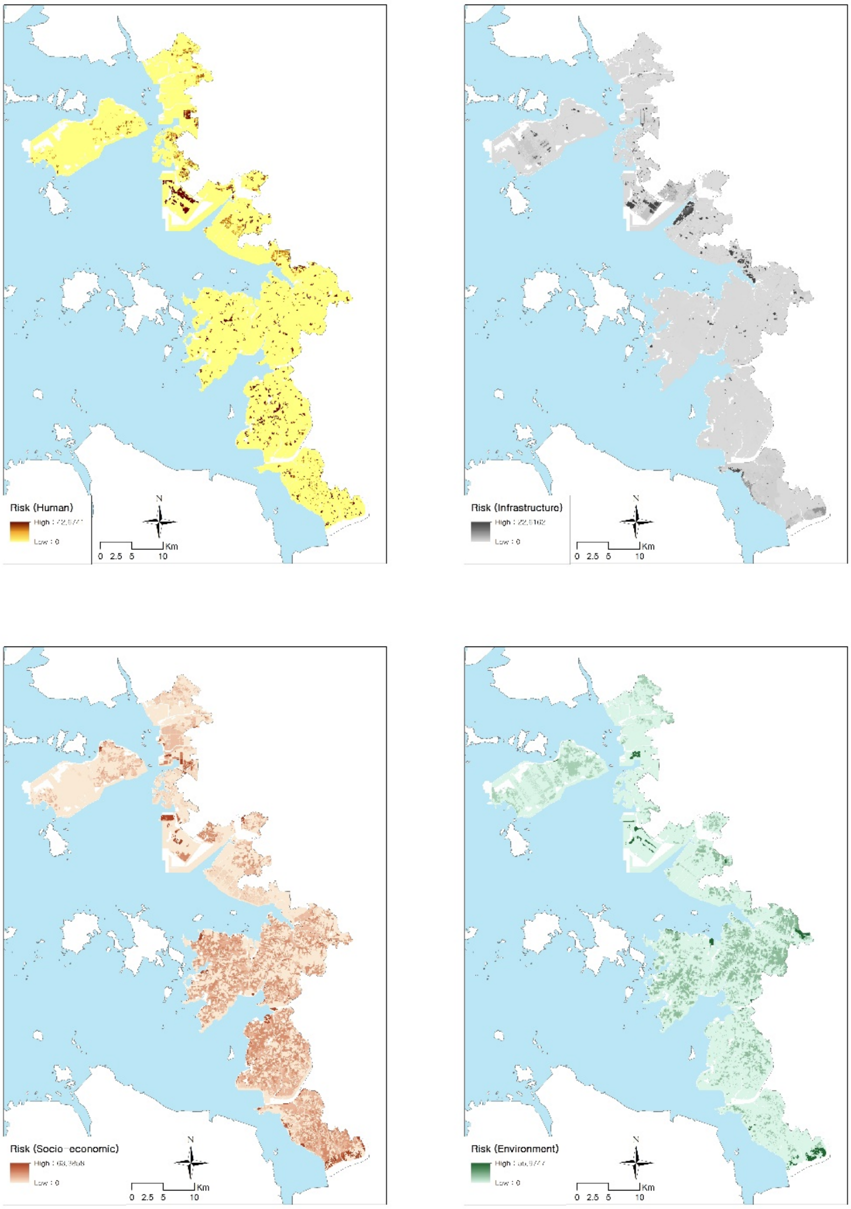


Figure 31. Risk of each dimensions using socio-economic indicators

$$Total\ Risk = [Risk(human) + Risk(infrastructure) + Risk(Socioeconomic) + Risk(Environment)]/4 \quad (13)$$

The results for each dimension are calculated (Figure 31). The total risk in this study is the combination of the results. The total risk is calculated by using the ratio of damage loss and Equation 13 is the calculation process of the final results (Figure 32). A risk map is created by using the 'total risk' result (Figure 33). The value of the result means that the probability of damage can be a maximum of 18.45% per year due to typhoon and rainfall.

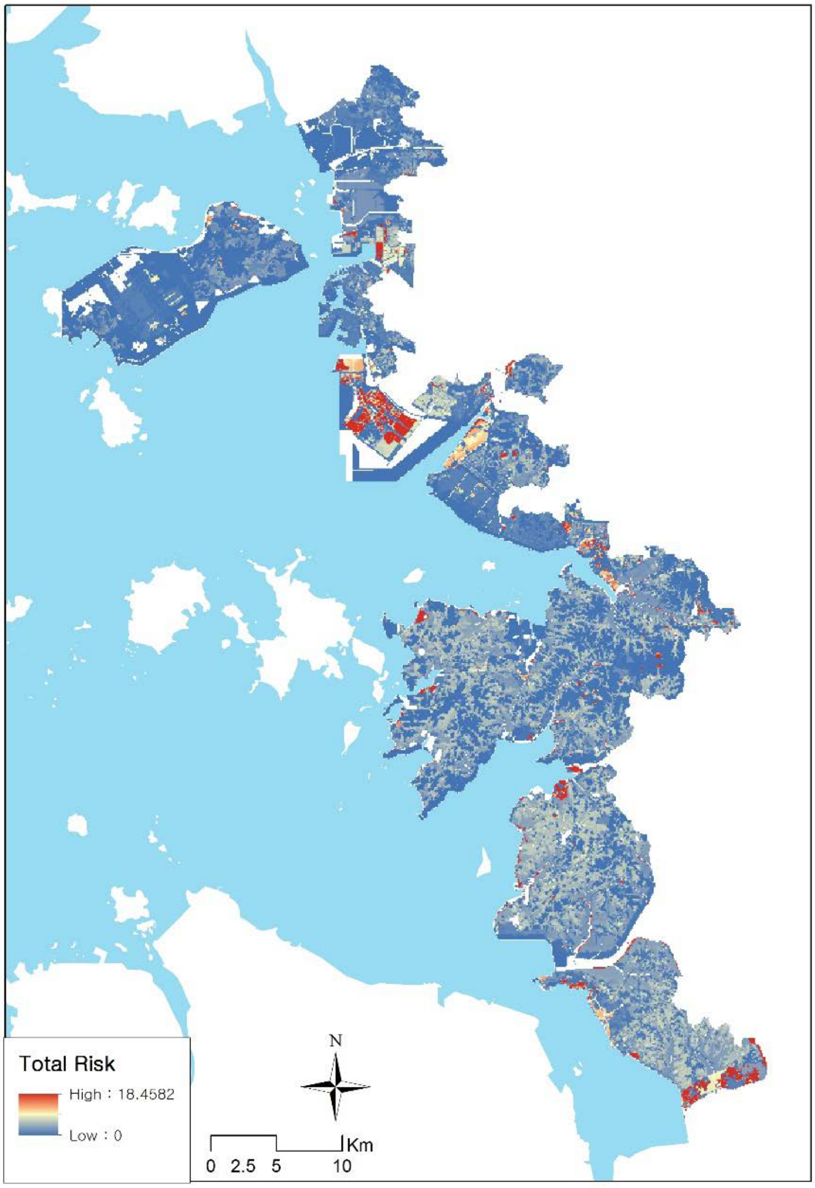


Figure 32. Total Risk

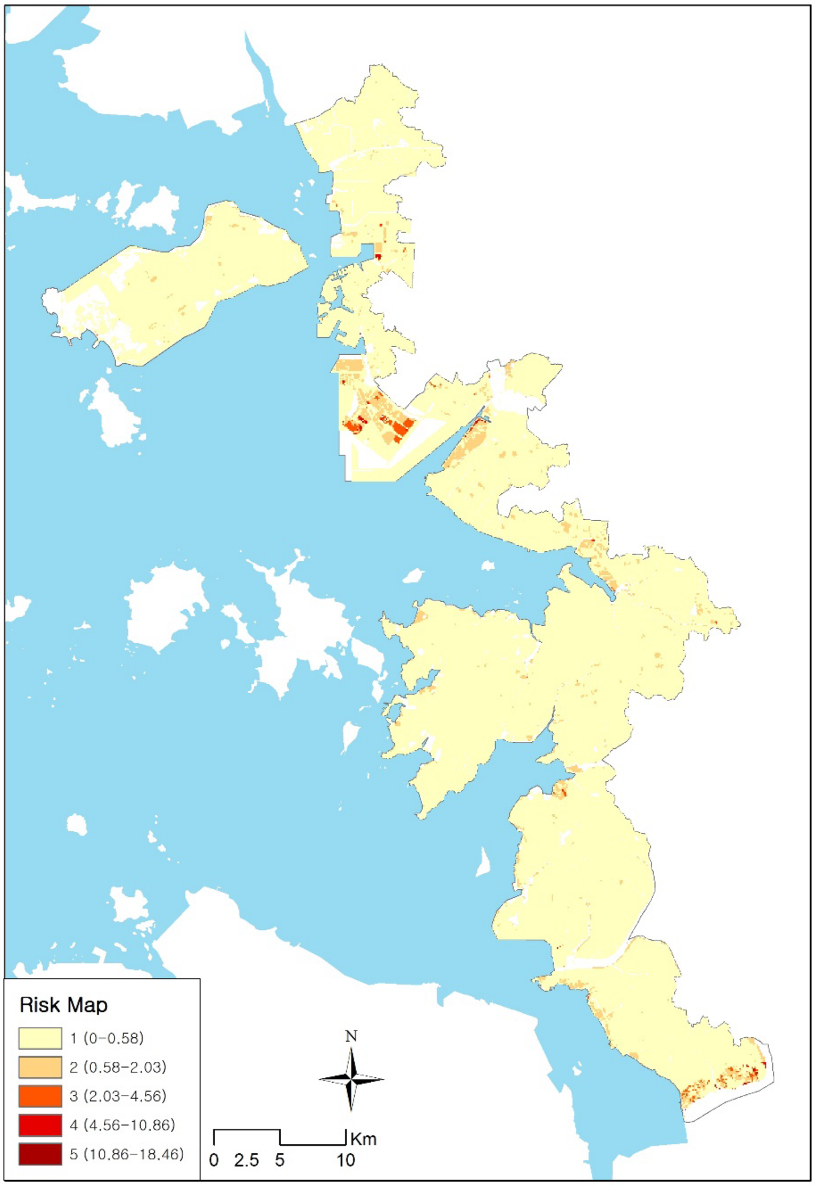


Figure 33. Risk Map

5. Discussion & Conclusion

5.1 Discussion

5.1.1 Identifying risk areas

From the risk map, risk areas are identified and characteristics of risk areas are looked up. As a result, Songdo-City in incheon, Baegot development-prearranged area in Siheung and region of Assan Lake in Hyeondeok, Pyeongtaek are resulted in risk areas as seen at Figure 34.

First of all, in case of Songdo-City, there is a study that it will be vulnerable and risk about inundation due to sea level rise and coastal hazard in the future (2100) (Cho et al., 2011). So, Songdo-City would be the crucial area for coastal management in the future. And Baegot development-prearranged area is located faced with Songdo-City and it is not developed yet, but developing plan has to be set up for preventing from coastal hazard. Also, the region of Assan Lake in Hyeondeok, Pyeongtaek has been usually flooded and almost consists of agricultural area. So, it has to be set up for minimizing damage of agriculture due to inundation.

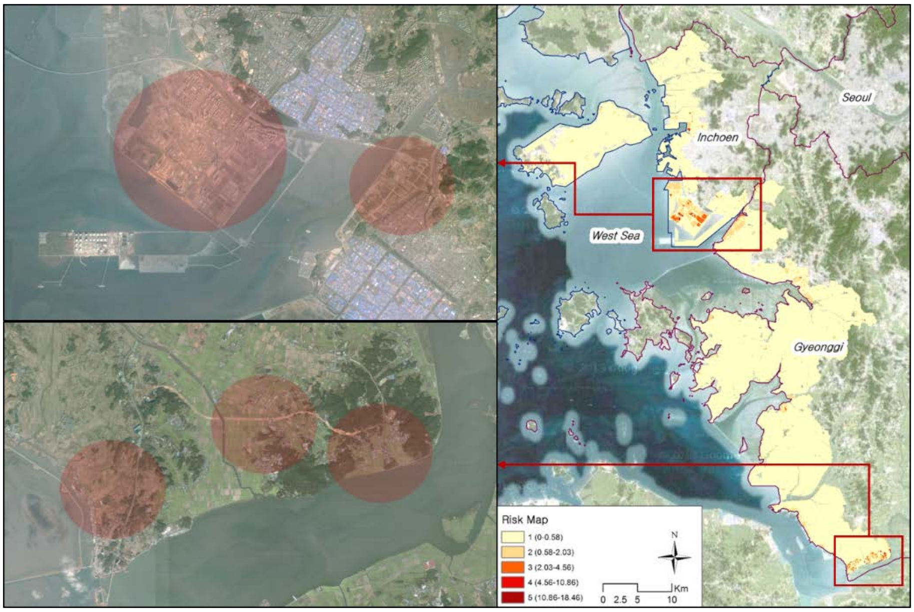


Figure 34. Risk map (right) and risk areas (left; google, 2014)

5.1.1 Comparison of results

This research evaluates the probability of coastal inundation through step1, 2 and the total risk is calculated by the process of step3. The probability of coastal inundation is estimated by using physical variables and its consequences called 'degree of damage' is calculated by using socio-economic indicators. So, if the result from step1,2 which is evaluated by using physical variables only and the final result from step 3 which is calculated by using physical and socio-economic indicators are compared, it could be known how socio-economic indicators effect the result and what it means.

Figure 35. An aerial photograph at Beagot development-prearranged area (2015-2017) in Siheung, Gyeonggi (Naver, 2010)

From the comparison with two results, the most remarkable thing is that risk areas evaluated by step 1, 2 could be not really at risk because of socio-economic indicators used at step 3. It means that the areas without socio-economic factors would be evaluated as not risk because of low 'degree of damage', although the probability of coastal inundation is high. In the other hands, the areas contained socio-economic factors could be calculated as at risk, although the probability of coastal inundation is low. From this, it could be recognized that the socio-economic indicators are crucial to analyze the risk.

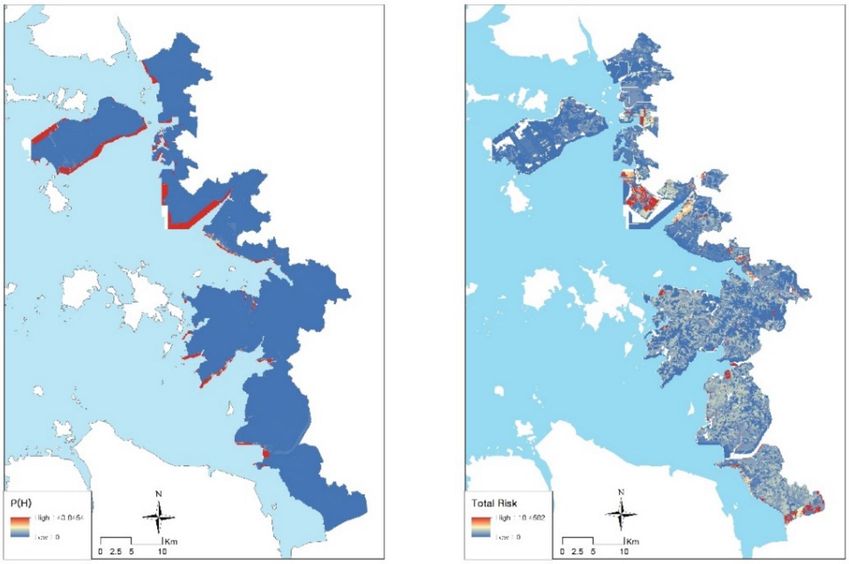


Figure 36. Comparison 'probability of coastal inundation (left)' with 'total risk (right)'

5.1.2 Limitation and significance

There are limitations in this study. First, the temporal scope in this study is from the past 30 years to the present. However, all of the past information is not analyzed as input data.

Second, this study does not offer the uncertainty provided by the Bayesian method. The variable itself considers the uncertainty in the Bayesian method since the input data is applied with a probability distribution. However, the uncertainty of the input data is not considered because the probability distribution of a value is not applied as input data in the process of calculating the prior probability in this study. The third limitation is related to the first limitation. In other words, this study cannot use all of the past 30 years of data in a temporal scope as input data, which cannot present the greatest advantages of the Bayesian method used in a study that applies uncertainty.

Fourth, dividing the situation into three categories by estimating the probability of coastal inundation due to typhoon and rainfall each is a limitation. The extent of the study area is different through various situations, which limits the results due to the dividing range in a common sense level.

Fifth, this study lacks verification. A flood map can be used to verify the results, which will be conducted by comparing a risk map and flood map in a following study.

In spite of these five limitations, the study complements some of the limitations of existing studies, and has academic significance by using Bayesian Networks (BNs) analyses. However, this study could not consider the uncertainty for the biggest advantages of the Bayesian method. The limitations of BNs are seen because the results are expressed as a map caused by the cell unit in the analysis process. Thus, cell units are expressed as a probability distribution map. The results are also expressed as a probability distribution. However, the uncertainty of a point is difficult to evaluate and can be considered an uncertainty in the results of the physical model.

Second, this study demonstrates that risk analysis is implemented by using physical and socio-economic factors at the same time. Existing studies usually considered one factor or qualitative analysis was implemented to reflect two factors. However, this study is implemented quantitatively when considering two factors.

5.2 Conclusion

The consequence for ‘degree of damage’ could be unpredictable along with an increased frequency and strength of a natural hazard and climate change. Thus, a prevention and preparation plan should be important for future hazards. Coastal areas consist of two characteristics, which are the natural ecosystem and social-economic factors. In the case of Korea, damages and losses occurred through typhoons and rainfall every summer. Thus, Korea needs to prevent these damages by implementing a prevention plan. However, prior to the implementation of a plan, we should know the areas with risk and vulnerability. Therefore, the objective of the research is to determine the risk areas created by typhoon and rainfall. A risk analysis as a conceptual method is used to evaluate the process, which is the combination of hazard and ‘degree of damage’ probability.

Coastal areas have a dynamic mechanism and a complicated process. Thus, various variables should be considered for analyzing risk from coastal hazards. Bayesian Networks are applied in this study. However, Bayesian Networks are not typically applied in risk analysis.

Bayesian Networks have some advantages. First, Bayesian Networks consider many variables at the same time and produce a visually simple network, which is a big advantage that is not seen in other methods. Thus, Bayesian Networks are easier to understand in comparison to a physical model. Second, Bayesian Networks could be presented in spite of the lack of data or information because of the approaching probability and uncertainty. An evaluation on coastal inundation possesses a complicated mechanism, and thus a risk analysis using Bayesian Networks is proper in this study.

The value of the results of the risk analysis using Bayesian Networks from coastal inundation means that the probability of damage could be a maximum of 18.45% per year due to typhoon and rainfall. The Songdo area (Incheon), Baegot development-prearranged area (Siheung) and the Assan Lake region (Hyeondeok, Pyeongtaek) resulted in risk areas (Figure 34). Also, the degree of damage is different according to whether there are or are not existing socio-economic indicators. However, the probability of hazard exists.

This study has two significant contributions, which are a risk analysis of coastal inundation using Bayesian Networks and a consideration of physical and socio-economic coastal area characteristics. The results of the risk analysis can be used to managing a coastal city. The study can also be used for Integrated Coastal Zone Management (ICZM) and as a political application.

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국문초록

최근 자연재해는 기후변화와 함께 빈도와 강도를 예측하기 점점 어려워 지고 있어 그 피해가 해가 갈수록 증가하고 있다. 특히, 연안지역은 미래에 기후변화로 인해 취약한 곳이 될 것이다. 우리나라는 삼면이 바다로 둘러 쌓여 있고 연안에 대도시가 많이 위치하고 있으며, 매해 폭우와 태풍과 같은 연안재해로부터 피해를 입고 있다. 따라서 연안지역에서의 재해로부터의 예방책이 반드시 필요하다. 하지만 계획에 앞서 어느 지역이 위험한지 알아야 한다. 그러기 위해서 연안지역의 특성을 반영하여 재해로부터의 위험한 지역을 찾아야 한다. 따라서 본 연구의 목적은 연안지역의 특성을 충분히 반영하여 폭우와 태풍과 같은 연안재해로부터 연안지역의 위험지역을 찾는 것이다.

연구의 공간적 범위는 해안선으로부터 1km 를 포함하고 있는 동단위의 행정구역으로 정하였다. 그리고 연안지역의 특성을 반영하기 위해 자연물리적, 사회경제적 특징을 동시에 반영할 수 있는 위험분석의 개념적 방법론을 따랐다. 위험분석은 위험요소의 발생 가능성과 그에 따른 피해 정도의 결합으로 설명된다. 이 두 가지 결합요소는 각각 연안지역의 자연물리적 특성과 사회경제적

특성을 반영한다. 그리고 본 연구의 내용적 범위는 여러 연안재해의 원인 중 폭우와 태풍으로 인한 연안재해로 한정하였으며 시간적 범위 또한 과거 30 년동안 일어났던 태풍 그리고 폭우 중 가장 영향력이 컸던 때의 값을 기준으로 하여 분석을 진행하였다.

위험분석을 수행하기 위해 본 연구에서는 베이지안 네트워크라는 새로운 확률통계적 접근기법을 사용하였다. 베이지안 네트워크는 베이즈 이론에 근거하여 만들어진 것으로 사전확률을 바탕으로 사후확률을 구하는 기법이다. 즉, 사전에 알고 있는 정보를 바탕으로 그 정보들 간의 관계를 설정하여 일련의 베이지안 기법으로 계산한 다음 이러한 정보를 바탕으로 사후에 어떻게 될 것인가를 구하는 것이다.

위험분석과정에서 먼저 위험발생 가능성은 크게 태풍으로 인한 침수위험발생 가능성과 폭우로 인한 위험발생 가능성으로 나뉠 수 있다. 태풍으로 인하 위험발생 가능성은 해일고를 산정하여 구하였고 폭우로 인한 위험발생 가능성은 강우량과 고도를 이용하여 구하였다. 각각의 위험발생 가능성은 크게 3가지 상황으로 나뉠 수 있으며 그에 따라 분석대상의 범위가 달라진다. 그리고 위험분석에서 피해 정도의 산정은 사회경제적 지표를 활용하여

구할 수 있으며 앞서 도출하였던 물리적 변수를 이용하여 구한 위험발생 가능성의 결과가 피해 정도 산정 과정에서 입력변수로 작용한다. 피해 정도 산정을 위해 사회경제적 지표를 크게 4 가지 차원으로 나누어 계산한다; 사람, 사회경제, 기반시설 그리고 환경. 4 가지의 차원에서 나오는 피해 정도를 모두 합쳐 최종결과물인 위험지역을 도출하게 된다.

최종결과물을 통해 사회경제적 요소의 유무에 따라 위험분석의 결과가 많이 달라지게 된다는 것을 알 수 있다. 그리고 위험지역으로 인천 송도신도시, 배곧도시개발예정지역 그리고 평택시 현덕면 아산호 일대 지역이 포함되었다. 인천 송도신도시는 향후 미래 해수면 상승으로 인해 침수위험지역으로 예측되는 다른 연구 결과가 있어 각별히 주의가 요구되는 지역이다. 개발예정지역의 경우 앞으로 연안재해로부터 피해를 많이 받지 않기 위해서는 적절한 사전대책이 필요하고 이를 고려하여 개발사업이 이루어 져야 한다. 아산호 일대 지역은 주로 저지대가 많아 과거에 상습침수 구역이 있는 것으로 보아 적절한 대책이 필요하나 주로 농경지가 많아 농경지 피해를 막기 위한 농업지역에 맞는 특정대책이 필요하다.

주요어: 연안재해, 연안지역, 위험분석, 베이지안 네트워크, 태풍, 폭우.

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